INFLUENCE OF WASTE TIRE RUBBER CRUMBLES AND FIBRES ON GEOTECHNICAL PROPERTIES OF CEMENTED CLAYEY SOIL

Ph.D. Thesis

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Influence of Waste Tire Rubber Crumbles and Fibres on Geotechnical Properties of Cemented Clayey Soil

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December 2018

DECLARATION

I, **Jitendra Singh Yadav,** declare that this thesis titled, **“Influence of Waste Tire Rubber Crumbles and Fibres on Geotechnical Properties of Cemented Clayey Soil”** and the work presented in it, are my own. I confirm that:

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This is to certify that the thesis entitled **“Influence of Waste Tire Rubber Crumbles and Fibres on Geotechnical Properties of Cemented Clayey Soil”** being submitted by **Jitendra Singh Yadav (2014RCE9028)** is a bonafide research work carried out under my supervision and guidance in fulfillment of the requirement for the award of the degree of **Doctor of Philosophy** in the Department of Civil Engineering, Malaviya National Institute of Technology, Jaipur, India. The matter embodied in this thesis is original and has not been submitted to any other University or Institute for the award of any other degree.

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ABSTRACT

The potential utilization of waste tire is nowadays has become a major challenge in front of the engineering community because of its deteriorating impact on the quality of the environment. About 1.5 billion tires are manufactured in the world per annum and 1000 million tires reach the cessation of their subsidiary life every year. This number can gain up to 1200 million tires per year, by the year 2030. In Indian scenario, 112 million discarded tires generated per year. These discarded tires are disposed to either landfills, stockpiled or burn off, which causes serious health and ecological problems. The recycling and reuse of these discarded waste tires can only minimize its environmental impacts. Many attempts have been made for its utilization in concrete, asphalt pavement, waterproofing system and membrane liner, etc. However, the knowledge about its utilization in geotechnical engineering is minimal and even scarce especially for cohesive soil.

In the present work, detailed experimental studies were carried out on utilization of waste rubber tyre in uncemented and cemented clayey soil. Two forms of waste rubber (i) crumbles and (ii) rubber fibres were used in this study. For this study, three percentages of cement (0%, 3% and 6%) and five percentages of rubber crumbles and rubber fibres were considered. The tests namely, compaction, unconfined compressive strength, split tensile strength, California Bearing Ratio, one dimensional consolidation, swelling pressure, and wet/dry cycles durability along with the XRD and SEM were conducted on clayey soil-cement-rubber crumbles/fibres mixtures to ascertain the suitability of rubber crumbles/fibres with cement stabilized clayey soil.

Following are the important conclusions of the study:

- The addition of rubber crumbles/fibres to clayey soil and clayey soil-cement mixtures decreases the maximum dry unit weight; the decrease is slightly more with the inclusion of rubber crumbles compared to rubber fibres. Similarly, the optimum moisture content of the mixtures decreases as the content of rubber crumbles/fibres increases. The optimum moisture content of clayey soil and clayey soil-cement mixtures incorporated with rubber fibres is less as compared to the same mixtures incorporated with rubber crumbles.

- Addition of rubber crumbles and fibres up to 5% and 2.5%, respectively improves the unconfined compressive strength and split tensile strength of clayey soil marginally. Further inclusion of rubber crumbles/fibres reduces the strength. Adding rubber crumbles and rubber fibres to clayey soil-cement mixtures reduce the unconfined compressive strength and split tensile strength. The rate of reduction in strength with inclusion of rubber crumbles is more than rubber fibres. The soaked specimens of clayey soil-cement mixture incorporated with rubber crumbles and rubber fibres show similar results as well.
- The California Bearing Ratio values for soaked condition of clayey soil and clayey soil-cement mixtures decreases as the content of rubber crumbles and rubber fibres increases. The use of rubber fibres in cemented clayey soil results in better outcomes in terms of reduction in rate of loss of California Bearing Ratio values as compared to rubber crumbles.
- Adding rubber crumbles and rubber fibres to uncemented/cemented clayey soil mixtures increases the compression index. Rubber fibres perform better than the rubber crumbles in reducing the rate of increase in compression index of mixtures.
- The swelling pressure of uncemented/cemented clayey soil mixtures incorporated with rubber crumbles and rubber fibres decreases as the rubber content increases. The inclusion of rubber fibres in cemented clayey soil has decreased the swelling pressure more as compared to rubber crumbles.
- The weight loss of cemented clayey soil incorporated with rubber crumbles mixtures are more than cemented clayey soil incorporated with rubber fibres.

To sum up, the maximum percentage of rubber crumbles and rubber fibres content that can be incorporated in cement stabilized clayey soil should not be more than 5% and 7.5% respectively. The proposed perspective for the disposal/utilization of waste tire would not only effectively mitigate the detrimental effects on health, environment, and ecological systems, but also efficient to enhance the engineering properties of cemented clay in totality. The incorporation of rubber crumbles/fibres in the uncemented/cemented clay can be one of the congenial methods for the disposal of this inexpedient waste because an enormous quantity of rubber waste can be consumed in the construction of voluminous structures such as fill material, backfill behind the retaining walls, embankments of rural roads, subgrade, sub base of rural roads, side slope of canal etc.

The thesis ends with suggestions for further work.

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NOTATIONS

ELT	End-of-Life Tires
CL	Low compressibility clay
CI	Medium compressibility clay
CH	High compressibility clay
ML	Low compressibility silt
MI	Medium compressibility silt
MH	High compressibility silt
SC	Clayey sand
CL-ML	Low compressibility clay with low compressibility silt
OH	High compressibility organic soil
SP	Poorly graded sand
W_L	Liquid limit
W_P	Plastic limit
I_P	Plasticity index
W_S	Shrinkage limit
MDD	Maximum dry density
OMC	Optimum moisture content
RLS	Rubber added lightweight soil
CGM	Composite geomaterial
ESR	Expansive soil rubber mixture
CD	Consolidated undrained
C_C	Compression index
UU	Unconsolidated undrained
C_S	Swelling index
C_R	Recompression index
C_V	Coefficient of volume change
CBR	California bearing ratio
TCLP	Toxicity Characteristic Leaching Procedure
NRA	National River Authority
EPA	Environmental Protect Agency
ANC	Acid Neutralization Capacity

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The term fine-grained soil stands for a soil having the particle size less than 0.075mm. It contains silt (0.075mm-0.002 mm) and clay (< 0.002 mm) fractions. Fine-grained soils are somehow troublesome to the geotechnical engineers because these soils exhibit noticeable changes in the physical properties with changes in moisture content. These materials can sustain heavy loads in the dry state, but become highly unstable in wet conditions. The shrinking and expanding of fine soils on drying and wetting could adversely affect structure rested upon them.

The non-plastic fine particles of fine-grained soil are termed as Silts. It is impervious in nature and highly susceptible to frost heaving. It has the tendency to saturate quickly and considered to have a viscous fluid like characteristic. The compaction of silty soils is very difficult. Dilatancy property of silt masses leads to the change of volume with change of shape. The plastic fines of fine-grained soils are termed as clay. In wet condition, it offers very low resistance to deformation. It is more impervious than silty soil and impossible to drain by ordinary means. Contrary to silt, it retains their volume with change of shape. The minerals present in clay belong to phyllosilicate group. The phyllosilicate group minerals have a plate-like structure. It consists of silica tetrahedron block and aluminium or magnesium octahedron block. In silica tetrahedron block, four oxygen or hydroxyl atoms surround the one ion of silicon atom tetrahedrally. The large number of tetrahedral joined to a sheet so that oxygen of the base of all tetrahedral are in a common plane and each oxygen belongs to two tetrahedral is called as silica tetrahedral sheet. In the case of aluminium or magnesium octahedron block, six oxygen atoms or hydroxyl groups enclose aluminium or magnesium ion octahedrally. The octahedral units are together into a sheet structure such that two layers of densely packed hydroxyls with cation between the sheets in octahedral coordination are called as dioctahedral or gibbsite sheet.

According to the mineralogy or structural groups, the clay is classified as kaolinite, illite, and montmorillonite. The kaolinite structural unit is made of gibbsite sheets joined to silica sheets through unbalanced oxygen atom. Successive layers of kaolinite are combined together with the hydrogen bonds. Due to strong hydrogen bond and lack of exchangeable cations, kaolinite shows negligible interlayer swelling on wetting. The most common clay mineral found in clay is illite. The essential structure of each unit is made of gibbsite sheet sandwiched between double silica sheets. Two units of illite minerals are weakly connect together by non-exchangeable ions of potassium. Montmorillonite clay mineral belongs to smectite group. Its structure is similar to illite mineral except that the units are bonded together by vander Waals forces. Montmorillonite mineral exhibits high swelling and shrinkage characteristics, depending upon the nature of exchangeable cations.

The mechanism of volume change in clay minerals is mainly related to the cation exchange capacity of minerals and diffused double layer. The negative oxygen or hydroxyl ions are predominant atoms present on the particle surface of soil. Positive ions or cations of water get attracted to the negative charge of clay particles to render the crystal electrically neutral. The amount of cations needed for neutralization of negatively charge ions present on the particle surface of the clay is called as cation exchange capacity. The diffused double layer is defined as the zone where net effect of attractive forces and repulsive forces decreases exponentially with the increase in distance from the clay particles surface.

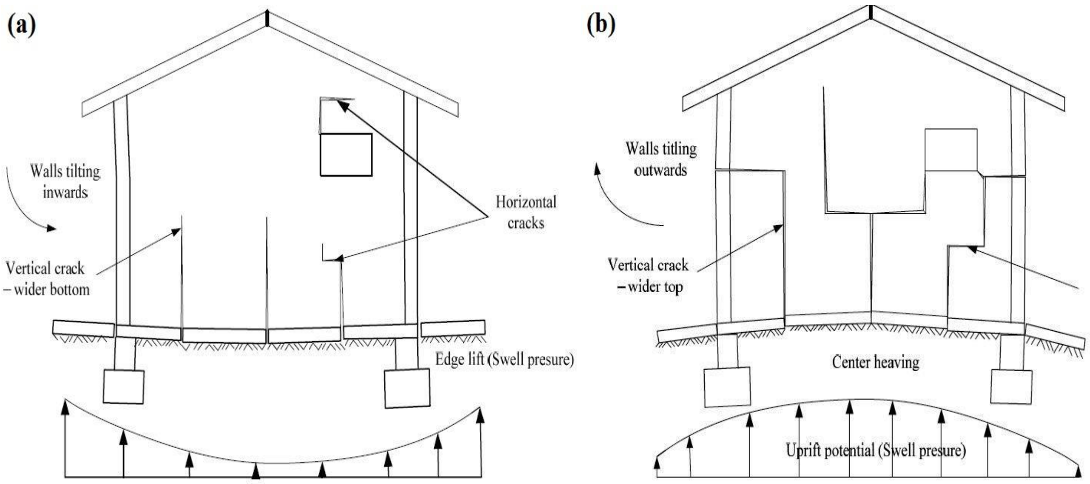


Fig.1.1(a) Edge heaves condition; **(b)** Centre heaves condition (Charles 2008)

The significant volume changes in clay due to drying and wetting of clay lead to structural damages especially in lightweight structures. The swelling of clay particle during wet season exerts an uplift force on foundation, and this phenomenon is known as edge heave as shown in Fig. 1.1(a). Whereas, shrinking of clay in dry season results into shrink at the edge and settlement of foundation. This effect is called as the edge-shrink effect. Additionally, the moisture gathered under the centre of foundation due to capillary action lead to rise of foundation from the centre. This condition is called, as centre-heave condition as shown in Fig. 1.1(b) and it is time dependent.

1.2 END-OF-LIFE TIRES

Over the last few decades, a steep growth in the generation of industrial and agricultural wastes has been witnessed due to substantial increase in the population. The waste rubber tires are among one of the most common industrial waste generated across the globe. The accumulated rubber tires inflict significant healths and environmental problem. The utilization or disposal of this inexpedient and hazardous waste in an environmental friendly way is one of primus challenge in front of engineering fraternity around the world to attain cleaner production.

“End-of-life tires” (ELT) or scrap tire is a term stands for a worn tire, which cannot be reused on vehicles for public traffic even after retreading and regrooving. Its proper disposal or utilization is a chronic issue for the environmental and human health especially in developing countries like China, India, etc. As these countries are riding on robust growth, which ultimately resulting in increase in number of vehicles on the road and so are number of tyres and it wastes. The quantity of ELT produced worldwide is enormous and it keeps increasing every year.

1.2.1 Production and utilization of waste rubber tires

According to published literature, the worldwide manufacturization of the tires is about 1.5 billion units(Thomas and Gupta 2015). According to IRSG (International Rubber Study Group)research, the total production of tires across the globe in year 2015 was 15.86 million tons, which was reported to be 1% more than the previous year. The rate of generation of ELT in developed countries is one passenger tire per person. According to an estimate, about 1000 million tires reach the cessation of their subsidiary life every year. More than 50% of waste tires are improperly dumped as landfill or garbage. The current rate of generation of discarded tire may increase this number up to 1200 million per year, by the year 2030 and ELT would increase to 5000 million(Thomas et al., 2016; Gupta et al., 2016). At present, USA, European Union, Japan, and India produce almost 88% of ELT of the world.

Utilization of ELT has been given most importance in countries like USA, European Union, Japan etc. Organizations like Rubber Manufacturers Association,Japan Automobile Tyre Manufacturers Association, and European Tyre & Rubber Manufacturers Association disseminate new technologies/applications through technical bulletins. According to the report of Rubber Manufacturers Association, US produced 167.8 million of tires in year 2015, and approximately 4038 thousand tons of ELT were generated. About 87.9% (percent by weight) of this was consumed as tire-derived fuel, civil engineering, and ground rubber applications. US scrap tire disposition in year 2015 is given in Fig. 1.2. In the year 2013, European Union produced 3.2 million tons of used tires as reported by European Tyre & Rubber Manufacturers Association (2015) of which only 2.5 million tones are either recycled or recovered (*End-of-life Tyre report, European Tyre & Rubber Manufacturers Association, 2015*). The Japan Automobile Tyre Manufacturers Association estimates that about 151.82 million tires were produced in 2015 and out of that, approximately 90% had been reused(Japan Automobile Tyre Manufacturers Association 2016). In Indian scenario, 112 million discarded tires are generated every year (Thomas and Gupta 2016). Until today, even the developed countries could not achieve the complete utilization of ELT. So, one can imagine the scenario of waste disposal and its utilization in developing and economically weak countries.

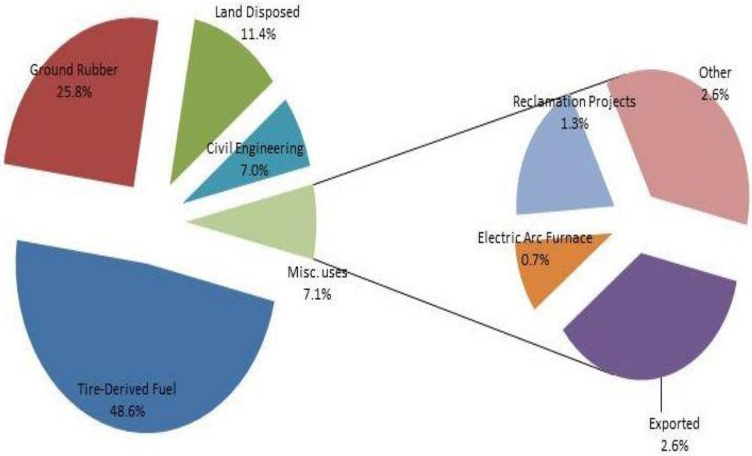


Fig. 1.2 US Scrap tires disposition in year 2015 (Rubber manufacturers association, 2016)

1.2.2 Problem associated with waste tire disposal

Incriminate generation and inefficient management of ELT across the globe lead to dangerous environment and health issues. Landfilling, stockpiling, and burning of ELT fuel for energy production are the common and conventional practice of disposal of this hazardous waste. These methods of ELT disposal are proven to be threat for ecological systems. The landfilling of ELT consumes large quantum of precious land in especially in city areas. The worn tires are incompressible material and have more than 75% space occupied by voids. It provides potential sites for breeding of rodents and gas collection. The methane gas trapped by tire exerts an upward float called buoyant which can damage or pierce the landfill liners. This phenomenon is known as bubbling effect of waste tires. The bubbling effect can also lead to contamination of water bodies and destroys the expedient bacteria of the soil. According to an estimate, about 279 millions of worn tires are stocked piled in US every year legally. Stockpiling of ELT has two prime detrimental effects: it creates sites for mosquitoes to breed and generates air pollution due to ignition. The stockpiles are capable of holding the water due to its impermeability for a longer version of time. This stagnated water creates an ideal and potential ground for breeding of mosquitoes and their larvae development. Aedes aegypti and Aedes albopictus, two species of mosquitoes are found predominately in the stockpiled nearby area. These two species cause diseases like Yellow Fever and Dengue in the human beings. To suppress the population of mosquitoes, mosquito abatement programs may be needed, if the stockpiling of the worn tires is not eliminated. The disposal of this deleterious waste as stockpiles is always at the high risk of ignition.

In the year 1983, it was seen that legally stockpiled tires of Virginia, burned for almost nine months and polluted the surrounded water sources. A large fire on the stockpiled tire in Stanislaus County, California as shown in Fig. 1.3 took 30 days to extinguish. It polluted the air and water severely and cost approximately 3.5 million dollars in damage and cleanup (USEPA, 1999). In the year 2008, the embankment made up of scrap tires (between 400,000 and 450,000) experienced combustion problems in Central Colorado of US (FHWA, 2008). Burning of stockpiled tires not only raises the temperature of surrounding environment, but also toxidizeses the air by emission of gasses like polyaromatic hydrocarbons, CO, SO_2, NO_2, and HCL. It also releases hazardous air pollutants (HAPs), such as polynuclear aromatic hydrocarbons (PAHs), dioxins, furans, hydrogen chloride, benzene, polychlorinated biphenyls (PCBs); and metals such as arsenic, cadmium, nickel, zinc, mercury, chromium, and vanadium. The burning of accumulated worn tires leads to breakdown of some rubber into an oily material which likelihood pollutes the surface and ground water. The extinguishment of fire in stockpiled tires is very tedious task. In the past, the utilization of water as fire extinguisher has proven to be futile effort due to unavailability of the adequate amount of water. Now days, the sand or dirt have been used for smothering of stockpiled tires, but it required heavy equipment to move the sand or dirt and has proven to be the costly ritual.

Emission of ELT for generation of energy for industries is reported to be less hazardous than open-air emission of tires. Both emissions of ELT as fuel or burning of stockpiled tires have acute and chronic effects on the health of firefighters and nearby residents. It leads to irritation of the skin, eyes, and mucous membranes, respiratory effects, central nervous system depression, and even cancer. Most of the developed and developing countries have imposed ban on landfilling, illegal stockpiling and open air burning of tires due its deleterious impact on the environment and human health. However, people are not much aware of these facts, especially in developing countries. Considering the environmental and health problems encounter in past during the disposal of ELT, the only viable solution is shredding or splitting tires. The disposal of ELT as shreds or splits not only occupies less ground but also eliminates the heaving problem associated with its disposal. It reduces land requirement upto 75% and transportation costs due to volume reduction and achievement of maximum hauling weight. The only demerit linked with shredded waste tires disposal is the additional processing step.

Fig. 1.3 Waste tire rubber stockpile fire in Stanislaus County, California fire, 1999 (USEPA, 1999)

1.2.3 Recycling Techniques

The convergences of ELT to various forms namely shreds, granulate (crumb), fibres (buffings), chips, and ash for its utilization or disposal is a very complex process which comprises of shredding and granulating by using special techniques and machineries. The application of various forms of ELT produced from different grinding processes depends on its particle shape, size, and texture. The two most common and efficient methods for grinding ELT are ambient and cryogenic grinding process. In ambient ELT processing, the size of ELT is reduced by grinding of rubber at or near ambient temperature (maximum 120^{o}C). In ambient process, the grinding of ELT is at ambient temperature which involves three basic processes, Granulator process, cracking mill process, and micro mill process. In the granulator process ELT of any size, even the whole tire is grounded by employing rotating blades and knives. The scrap tires so produced are of cubical and uniform shape ranges from 9.5 mm to 2 mm. In cracking mill process, tire crumbs that are also known as grounded rubber having particle size between 4.75 mm to 425 μm are produced. It is a sequential process consisting of coarse grinding, primary crack mill, secondary crack mill, cleaning, and screening.

In coarse grinding, the ELT are subjected to shredder for size reduction. It reduces the size of ELT into 50 mm shreds. The primary crack mill consist two counter rotating corrugated steel drums, which grinds the 50 mm shreds into 12.5 mm particles, and separate out metals and fibre layers by using several magnetic and air gravity separator systems. The rubber shreds of 12.5 mm size are further subjected to the secondary cracking mill for size reduction up to 20 meshes by feeding it into the secondary cracking mill. After desired size reduction, the rubber particles are subjected to secondary magnetic separation system for removal of remaining steel. The oversize materials are separated out by screening and return to mill for further reduction.

Very fine rubber particles ranging between 425 μm to 75 μm is obtained by micro mill processing. Size reduction through this process is time dependent. The scrap tires obtained from ambient processing are of fragile nature because the process implements no cooling. Rubber particles obtained from this process have a rough texture and cut surface shape (Fig. 1.4(b)). Fig. 1.4(a) shows the sequential diagram of ambient grinding process.

In cryogenic ELT processing, the rubber chips of 2 inches or smaller size are subjected to size reduction. The rubber tires are frozen to temperature below -80 ^{o}C by using liquid nitrogen in a tunnel style chamber until it becomes brittle in nature before size reduction. Then rubber tires are subjected to impact loading in hammer mill. Hammer mill reduced the size of scrap tires as per desire. The size reduction after hammer mill ranges between ¼ inches to 30 meshes. The rubber obtained from this method is free from fibres or steel and is of high yield. If any steel or fibres have remained in the rubber, it is separated out by using magnet, aspiration and screening. Rubber particles obtained from this process have a smooth surface and sharp edge (Fig. 1.5(b)). The sequential diagram of cryogenic grinding process is illustrated in Fig. 1.5(a).

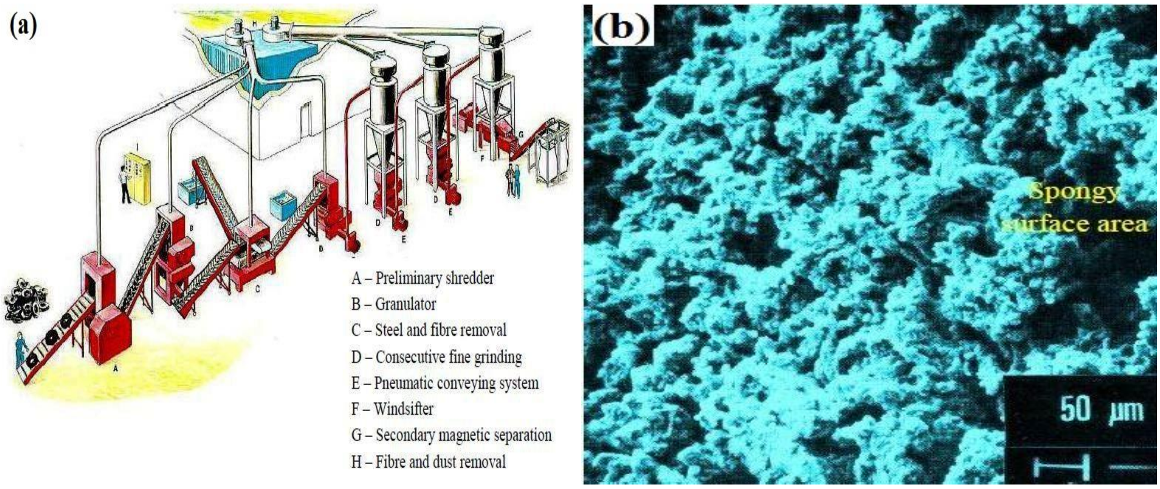


Fig. 1.4(a) Typical ambient granulating system (Reschner 2008); **(b)** surface appearance of ELT for ambient granulating process (Oliver 1981)

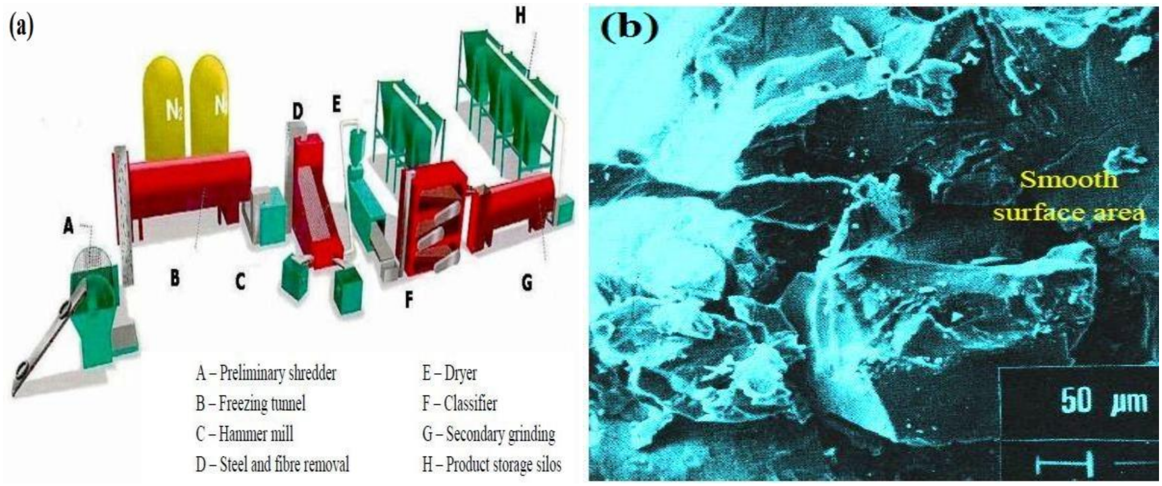


Fig. 1.5(a) Typical cryogenic grinding system (Reschner 2008); **(b)** surface appearance of ELT for cryogenic grinding process (Oliver 1981)

Wet grinding and Hydro jet size reduction are two additional techniques that are used for size reduction. These techniques are less common proprietary processes for size reduction. The wet-grinding process is used to obtain the rubber of 40 mesh or finer size. In this process, rubber is mixed with water to form a slurry. This slurry is subjected to size reduction in micro-milling machine. After achieving the desired size, the water is removed from slurry and rubber is subjected to drying process. In Hydro jet size reduction technique, pressurized water is used for reduction of rubber particles to very fines particles. The retreading process of worn tire produces tire buffings. Its size ranges between 710 µm to 25 µm. The granules or buffings derived from ELT by using various recycling techniques should be free from steel, fibres and any other inert contaminants such as dust, glass, or rocks etc for their field application.

1.3. PROPERTIES OF RUBBER TIRE WASTES

1.3.1 Classification

The behavior of fine-grained soil-rubber tire wastes mixture is significantly influenced by the size of rubber tire. The two common established standards are enlisted below which are used worldwide for the nomenclature of rubber tire wastes.

- ASTM D 6270, "*Standard Practice for Use of Scrap Tires in Civil Engineering Applications*"
- CEN Workshop Agreement (CWA) 14243-2002 (CWA, 2002)

According to ASTM D6270-08, 2014, rubber tire wastes may be classified as particulate rubber (buffing rubber, granulated rubber, ground rubber, and powdered rubber), rough shred, tire derived aggregate (TDA), tire shred, and whole tire. Table 1.1 summarizes the established standard nomenclature and size of rubber tire wastes as suggested by ASTM D6270-08, 2014.

Table 1.1 Nomenclature and sizes of rubber tire wastes according to ASTM D6270-08, 2014

Designation	**Shape**	**Size**
Granulated rubber	non-spherical	Below 425 µm (40 mesh) to 12 mm
Ground rubber	non-spherical	Below 425 µm (40 mesh) to 2 mm
Powdered rubber	non-spherical	Below 425 µm (40 mesh)
Rough shreds	-	Larger than 50 mm x 50 mm x 50 mm, but smaller than 762 mm x 50 mm x 100 mm
Tire chips	basic geometrical shape	Between 12 and 50 mm
Tire derived aggregate	basic geometrical shape	Between 12 and 305 mm
Tire shreds	basic geometrical shape	Between 50 and 305 mm
Whole tire	-	Unprocessed

In the CEN Workshop Agreement (CWA) 14243-2002 (CWA, 2002), Post-consumer tyre materials and applications, developed by European Committee for Standardization rubber tire wastes, are classified as buffings, size reduced materials (whole tyre, cuts, chips, granulate, powder, and fine powder), reclaim/ devulcanisates (devulcanisates, rubber reclaim, and surface modification) and process specific materials (pyrolytic products) according to the material outputs. According to this classification, each product has been described by a single letter code. The specific code and sizes of each material are presented in Table 1.2.

Table 1.2 Nomenclature, code, and sizes of rubber tire wastes according to CEN Workshop Agreement (CWA) 14243-2002 (CWA, 2002)

Designation	**Code and shape**	**Size**
Whole tyre	W	Untreated
Cuts	X, irregularly	Formed pieces > 300 mm
Shred	S, irregular pieces	≈ 50 mm to ≈ 300 mm in any dimension
Chips	C, irregularly shaped	Approximately 10 mm to 50 mm
Granulate	G	Between approximately 1 mm and 10 mm
Powder	P	Under 1mm
Fine powders	F, finely dispersed particles	< 500 μm
Buffings	B, elongated particles	1-25 mm from car and 1-40 mm from truck
Reclaim	R	Depends on input
Devulcanisate	D	Depends on powder
Pyrolitic char	Y	<10 mm
Carbon products	Z	<500 μm

1.3.2 Physical and Mechanical properties

Specific gravity, water absorption, elastic modulus, tensile strength, etc are the prominent physical properties of rubber tire wastes. The specific gravity of rubber tire waste may vary from 0.8 to 1.4 as mentioned by many investigations. The water absorption capacity of rubber tires is about 4%. Typical properties of rubber tire waste are summarized in Table 1.3 as documented by the researchers. The properties of rubber mentioned in CEN Workshop Agreement (CWA) 14243-2002 (CWA, 2002) are tabulated in Table 1.4.

Table 1.3 Physical properties of rubber tire wastes used by different authors

Physical properties	**Akbulut et al., (2007) Kalkan, (2013)**	**Tajdini et al., (2016)**
Density, (Mg/m^3)	1.153 - 1.198	-
Elastic modulus (MPa)	1.97 - 22.96	1 - 2
Tensile strength (MPa)	28.1	-
Extent at failure (%)	44 - 55	-
Softening temperature (°C)	175	-
Friction angle (^{0})	-	19 - 26
Cohesion (kPa)	-	1 -5
Poisson ratio	-	0.2 - 0.35

Table 1.4 Properties of rubber CEN Workshop Agreement (CWA) 14243-2002 (CWA, 2002)

Properties	**Value**
Compacted unit weight	2.3 - 4.8 kN/m^3 compared to soil at 15.6 - 19.5 kN/m^3
Compacted dry unit weight	1/3 that of soil
Compressibility	3 times more compressible than soil
Density	1/3 to 1/2 less dense than granular fill
Durability	Non-biodegradable
Earth pressure	Low compared to soil or sand, up to 50% less
Friction characteristics	Higher compared to soil
Horizontal stress	On weak base: lower than with conventional backfill
Modulus in elastic range	1/10 of sand
Permeability	Greater than 10 cm/s
Poisson's ratio	0.2-0.3 corresponding to *Ko* values of 0.3 - 0.4
Specific gravity	1.14 - 1.27 compared to soil at 2.20 - 2.80
Thermal insulation	8 times more effective than gravel
Unit weight	Half the typical unit weight of gravel
Vertical stress	On weak base: smaller than granular backfill

By using scanning electron microscopy (SEM) technique, the particle shape and surface characteristics of rubber tire wastes can be studied. Fig. 1.6 shows the SEM images of various waste tire wastes used by the investigators in their research work.

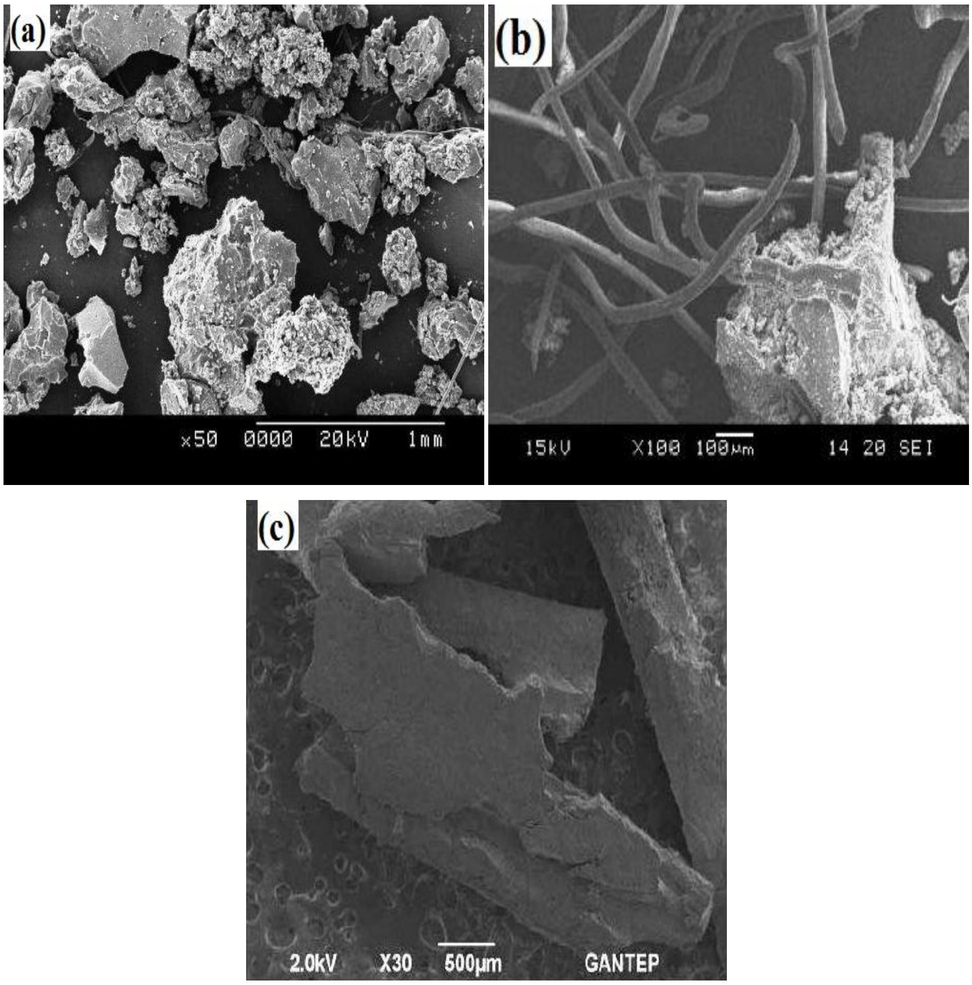


Fig. 1.6 SEM images of rubber tire wastes used by various investigators **(a)**Kim and Kang, (2011); **(b)**Wang and Mei, (2012); **(c)** Cabalar et al., (2014)

1.3.3 Chemical properties

The main chemical components of rubber tire wastes are Styrene butadiene copolymer and Carbon block. Other minor constituents include extender oil, zinc oxide, stearic acid, and Sulphur. Typical chemical composition and oxidization element are tabulated in Table 1.5 and Table 1.6.

Table 1.5 Component (%) of rubber tire wastes used by different authors

Component (% by weight)	**Akbulut et al., (2007) Kalkan, (2013)**
Styrene butadiene copolymer (%)	62
Carbon block (%)	31
Extender oil (%)	1.9
Zinc oxide (%)	1.9
Stearic acid (%)	1.2
Sulphur (%)	1.1
Accelerator (%)	0.7

Table 1.6 Oxide Concentration (%) of rubber tire wastes used by different authors

Oxide Elements (% by weight)	**Ho et al., (2011) Ho and Chan, (2010)**	**Lekan and Ojo, (2013)**
Al_2O_3	16.20	7.8
CaO	44.87	13.3
Fe_2O_3	1.28	11.4
PbO	0.87	-
SiO_2	20.50	33.8
SO_3	1.1	1.6
ZnO	6.96	-
MgO	-	6.4
Na_2O	-	1.4
K_2O	-	1.1
TiO_2	-	1.0
LOI	-	12.5

1.4 SCOPE OF THE WORK

Disposal of discarded waste tires is one of the major problems faced by the industries and Government of many countries. The common practice used for the disposal of waste tire such as stockpiles, landfills and burning are considered as a big danger to the health of humans and ecological systems. The stockpiling provides breeding sites for mosquitoes and rodent, whereas heaving of ground has been faced with landfills disposal of waste tires. The poisonous gasses liberated by the burning of waste tire, when used as a fuel in the industry causes serious health hazards to population living nearby that area. Many countries have banned the use of tires as a fuel for the industries. Indian government restricted the import of used /retreaded Tires since April 2006. In India, at present only 18% of the scrap tire are beneficially and environmental safely reused or recycled (Kaushik et al., 2010). Therefore, timely action regarding the safe disposal of waste tires is necessary, keeping in view the environmental problems and health hazards associated with it. One of the common and feasible ways to utilize these waste products is to explore their use in construction of roads, highways, embankments and a fill material. On the other hand, due to rise in population and an increase in infrastructure growth in metropolitan areas, there is a dramatic increase in the prices of land and lack of suitable sites for development. Therefore, now-a-days construction is also being carried out on marginal sites having extremely poor ground conditions like soft clays that were earlier considered unsuitable due to their poor strength and high compressibility. Such soils, when loaded, cause excessive settlements and early failure of structures. It is a challenge to the geotechnical engineer to improve mechanical properties of clayey soil by using stabilization and reinforcement techniques at a reasonable cost.

The problems associated with disposal of waste tires and stabilization of problematic soft/weak soils has encouraged the authors to do this investigation. The use of discarded waste tires as an engineering material is gaining popularity among civil engineering fraternity due to its low density, high strength, hydrophobic nature, low thermal conductivity, durability, resilience and high frictional strength, which are essential from the geotechnical engineering perspective.

Thus, in this scenario, it is planned to conduct a detailed study on the behaviour of clayey soil mixed with cement and waste rubber tire crumbles and fibres so that their use in low volume roads as well as lightweight backfill material of retaining walls could be thoroughly assessed.

In this research, a detailed systematic experimental study on the behaviour of clayey soil-cement-rubber crumbles/fibres mixtures has been attempted. To this end, laboratory tests namely, modified Proctor, unconfined compression, split tensile strength, California Bearing Ratio, one-dimensional consolidation, swelling pressure and wet/dry cycles durability were performed on the mixtures of clayey soil containing four rubber crumbles/fibres contents (2.5%, 5%, 7.5%, and 10%, by dry weight) and two cement contents (3%, and 6%). Mineralogical and micro-structural analyses of the mixes were carried out through X ray diffraction and scanning electron microscopy (SEM) to get the better intuition of the composites behaviour. The Multiple linear regression analysis (MLRA) was also carried out for all performed tests to establish the relation between dependent and independent variables.

1.5 OBJECTIVES OF THE STUDY

With the above in view, the present study was planned to understand the application of cement stabilized clayey soil mixed with rubber crumbles and rubber fibres with variation in rubber content and curing periods. The behavior of mixtures was examined thoroughly through modified proctor compaction, unconfined compression strength, split tensile strength, California Bearing Ratio, one-dimensional consolidation, swelling pressure, wet/dry durability, mineralogical, and microscopic studies. More specifically, the proposed research includes

a) To assess the compressibility characteristics of clayey soil mixed with cement and randomly oriented rubber crumbles and fibres.
b) Evaluation of strength characteristics of clayey soil mixed with cement and randomly oriented rubber crumbles and fibres.
c) A study of swelling pressure and durability aspect of clayey soil mixed with cement and randomly oriented rubber crumbles/fibres.
d) Microscopic and mineralogical studies on the clayey soil mixed with cement and randomly oriented rubber crumbles/fibres.

An extensive laboratory-testing programme was devised and the results are critically analyzed to assess the possible application of these waste materials in low volume roads, embankments, fill material as well as lightweight backfill material of retaining walls. All experimental work was conducted at Geotechnical Laboratory and Material Research Centre, Malaviya National Institute of Technology Jaipur.

1.6 ORGANIZATION OF THESIS

The thesis has been written in eight chapters. Brief details of each chapter are as follows:

Chapter 1: Introduction

This chapter provides an introduction to the fine-grained soil and the problem associated with it. This chapter introduces the production and utilization of End-of-life tires. The overall scope of research work has been explained.

Chapter 2: Literature Review

This chapter presents a brief review of relevant literature of the work carried out by various investigators.

Chapter 3: Experimental Work

The chapter describes setup, apparatus, instrumentation, test methods and procedures adopted for various tests. The detailed properties of materials used (soil, cement, rubber crumbles and rubber fibres) in the study is discussed.

Chapter 4: Influence of waste rubber crumbles/fibres on the geotechnical properties of clayey Soil

This chapter presents the results of modified proctor compaction, unconfined compression strength, split tensile strength, California Bearing Ratio, one-dimensional consolidation, swelling pressure, wet/dry durability, and microscopic study carried out on clayey soil-rubber crumbles/fibres mixtures.

Chapter 5: Assessment of geotechnical properties of cemented clayey soil incorporated with waste rubber crumbles

This chapter presents the details and results of modified proctor compaction, unconfined compression strength, split tensile strength, California Bearing Ratio, one-dimensional consolidation, swelling pressure, wet/dry durability, mineralogical and microscopic tests carried out on clayey soil-cement-rubber crumbles mixtures.

Chapter 6: Effect of waste rubber fibres on the geotechnical properties of clayey soil stabilized with cement

Chapter 6 presents the details and results of modified proctor compaction, unconfined compression strength, split tensile strength, California Bearing Ratio, one-dimensional consolidation, swelling pressure, wet/dry durability, and microscopic tests carried out on clayey soil-cement-rubber fibres mixtures.

Chapter 7: Comparative Study on the effect of waste rubber crumbles and rubber fibres inclusion on the geotechnical properties of clayey soil stabilized with cement

Chapter 7 is focused on the comparison of the results of modified proctor compaction, unconfined compression strength, split tensile strength, California Bearing Ratio, one-dimensional consolidation, swelling pressure, wet/dry durability, and microscopic tests of uncemented/cemented clayey soil mixed with rubber crumbles and rubber fibres presented in Chapter 4, 5, and 6. The results of uncemented/cemented clayey soil mixed with rubber crumbles and rubber fibres have been compared with Indian standards for its application in low volume traffic roads, embankments, and lightweight backfill material of retaining wall.

Chapter 8: Conclusions

This chapter presents an overall summary of work carried out and brings out the salient conclusions. The scope of future studies has also been included.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

The rapid urbanization and industrialization have resulted in generation of an enormous quantity of municipal and industrial wastes such as fly ash, rice husk-ash, incineration ash, bottom ash, ceramic waste, plastic waste, waste rubber tires, etc. Disposal of these solid wastes in economically viable and environmental friendly way have become primary challenge and problem, especially for developing countries. Despite of regulations for hazardous waste management, these wastes are disposed of on land or discharged into water. Thus, it becomes a substantial source of environmental pollution and health problems. The discarded waste tire is among one of the most deleterious waste material of this era.

Disposal of abandoned, worthless rubber tires is becoming prime challenge and problem across the globe (Lv et al., 2015; Angelin et al. 2015). In recent years, the civil engineer’s community has shown a tremendous interest on utilization of discarded waste tires for civil engineering applications. Many attempts have been made for the utilization of waste tires in concrete, asphalt pavement, water proofing system, etc **(**Tortum et al., 2005; Huang et al., 2005; Cao, 2007; Pacheco-Torgal et al., 2012; Shu and Huang 2013).In last 20 years, many research endeavours have been made towards the use of discarded waste tires for geotechnical purposes such as reinforcement of soil, stabilization of earthen slopes, backfilling lightweight material of retaining walls, etc. The problems of settlement and cracking were faced in the past by authors (Humphrey, 1996; Gacke et al., 1997) due to the development of exothermic reaction, when the pure tire shreds were utilized for civil engineering applications. Hence, in recent years, the research has been directed towards its utilization as partial replacement of soil. A significant amount of research has been carried out by the geotechnical fraternity on the effect of waste rubber tire inclusion on the geotechnical characteristic of soil(Foose et al., 1996; Tatlisoz et al., 1998;Ghazavi and Sakhi, 2005;Rao and Dutta, 2006;Kim and Santamarina, 2008). Most of the studies reported in literature are concise on the behaviour of sandy soil-waste rubber tire.

Geotechnical properties of sand- rubber tires (different types as classified by ASTM D 6270-98) mixtures depend on the ratio of scrap tire and sand(Ahmed, 1993; Bosscher et al., 1997; Foose et al., 1996; Edil and Bosscher, 1994; Tatlisoz et al., 1998; Zornberg, 2004;

Ghazavi et al., 2005; Rao and Dutta, 2006; Kim and Santamarina, 2008; Lee et al., 2010), confining pressure in triaxial tests(Ahmed, 1993; Zornberg, 2004; Rao and Dutta, 2006; Masad et al.,1996; Youwai and Bergado et al., 2003), normal stress in direct shear tests(Bosscher et al., 1997; Foose et al., 1996; Edil and Bosscher, 1994; Tatlisoz et al., 1998; Ghazavi et al., 2005), unit weight of the sand matrix(Bosscher et al., 1997; Foose et al., 1996; Edil and Bosscher, 1994; Zornberg, 2004; Ghazavi et al., 2005), and aspect ratio of tire shreds or chips (Zornberg, 2004; Ghazavi et al., 2005; Rao and Dutta, 2006).

The incorporation of waste tires in sand (i) leads to lowering the unit weight of the composite because of the low specific gravity of rubber tire particles; (ii) improves the shear strength and angle of friction because of development of apparent cohesion due to interlocking of the sand and shredded tires; (iii) results in lesser compressibility because of the elastic behaviour of sand-rubber mixtures.

Engineers, because of its low strength, high compressibility, and low permeability, always consider the construction of structures like tall buildings, dams, retaining walls, roads, etc on fine-grained soil as an arduous task. The clayey soils are considered unsuitable for construction activities due to its low resistance to deformation under wet conditions, poor drainage, high swelling, and shrinkage properties. The utilization of stabilizing agents such as cement or lime can improve the geotechnical properties of fine-grained soil, which is well documented in the literature. However, the addition of cement or lime increases the stiffness and brittleness of the fine-grained soil(Tang et al., 2007; Fatahi et al., 2012;Nguyen and Fatahi, 2016;Kumar and Gupta, 2016). These issues of stabilized fine-grained soil can be overcome with the addition natural fibres like coir, jute, etc or synthetic fibres like polypropylene, polyester, nylon, glass, etc. The waste rubber tires could be used for confinement or reinforcement of fine-grained soils because of its high durability, strength, resiliency, and greater frictional resistance. The information about behaviour of fine-gained soil mixed with various forms of discarded waste tire such as chips, shreds, fibres, and crumb is very scarce. The chapter briefly reviews literature on fine-grained soil-waste rubber tire mixtures.

2.2 LITERATURE REVIEW OF FINE-GRAINED SOIL CONTAINING WASTE RUBBER TIRES

This chapter summaries and reviews the most relevant knowledge on effect of incorporation of various forms of waste rubber tires namely shreds, granulates, chips, fibres, and powder on

Atterberg's limits, compaction, strength, consolidation, swelling, permeability, California Bearing Ratio, leachability, dynamic and durability properties of fine-grained soils. The details of type of fine-grained soil and form of rubber wastes, its size and content along with other additives if any used by different authors is briefly summarized in Table 2.1.

Table 2.1 Soil type, rubber waste type, size and content and other additives (if any) used by different authors

Authors	**Soil type**	**Waste type**	**Size**	**Rubber content (%)**	**Other additives**
Al-Tabbaa et al., (1997)	Kaolin, bentonite	Shreds	Three size ranges of 1-4mm, 4-8mm, and 8-12mm	2 to 20	Sand-60% and lime-5%
Al-Tabbaa and Aravinthan, (1998)	CL	Shreds	Two size ranges of 1-4mm, and 4-8mm	6-8, and 10-15	-
Cokca and Yilmaz, (2004)	Bentonite	Granular	75-850 µm	0, 1, 3, 5, 7, 9 and 10	Fly ash-90%
Özkul and Baykal, (2006)	CL	Buffings	Length and diameter of 4-15, and 0.3-1.5 mm	10	-
Cetin et al., (2006)	CL	Chips	Two sizes of 4.75- 2 mm and passing 0.425 mm	10, 20, 30, 40, and 50	-
Özkul and Baykal, (2007)	CL	Buffings	Length and diameter of 2-25, and 0.3-3.6 mm	10	-
Seda et al., (2007)	CH	Shreds	Less than 6.7 mm	20	-
Akbulut et al., (2007)	CH	Fibres	Three size ranges of 2-5 mm, 5-10 mm, and 10-15 mm	1, 2, 3, 4, and 5	-
Ho et al., (2010, 2011)	Kaolin	Chips	2-5 mm	0, 5, 10 and 15	Cement-2 and 4 %
Patil et al., (2011)	CH	Granular	0.6 to 0.1 mm	-	Silica sand
Kim and Kang,	CL	Crumbles	0.1–2 mm	0, 25, 50, 75,	Bottom ash-

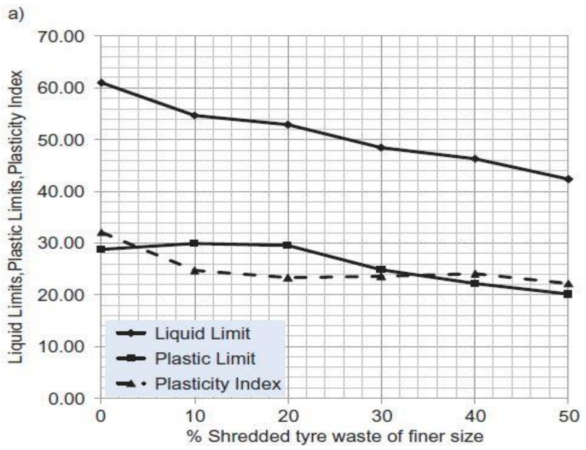
(2011)				100	100%
Chan, (2012)	CH	Granular	6 mm	1,2, and 4	Cement-20% Cement-2 and 4%
Trouzine et al., (2012)	CL	Fibres	5-30 mm length and, average length of 7 mm	10, 20, 25, and 50	-
Jafari and Esna-ashari, (2012)	CL	Fibres	20 mm length	0.5, 1, and 1.5	Lime- 4%, and 8%
Kalkan, (2013)	CH, MH	Fibres	Length, thickness, and width of 5-10, 0.25-0.50, 0.25-1.25 mm	1,2,3, and 4	Silica fume- 10 and 20%
Srivastava et al., (2014)	CH	Shreds	Two sizes ranges of 2.0–0.075 mm and 4.75–2.0 mm	5, 10, 15, 20, and 30	-
Otoko and Pedro, (2014)	CI, CH	Fibres	10-20mm length and 1.5-2.5mm thickness	5, 10, and 15	Cement-2, and 4%
Cabalar et al., (2014)	CI	Buffings	0.6-4.75 mm	0, 5, 10, and 15	Lime-0%, 2%, 4%, and 6%
Priyadarshee et al., (2015)	CL	Crumbles	4.75-0.6 mm	1, 2, 5, 10, and 20	Fly ash
Wang and Song, (2015)	CL	Crumbles	Two sizes of 30/40 mesh and 60/80 mesh	5,10,15, and 20	Cement-7%, 15%, 20%, and 25%
Signes et al., (2016)	CH	Crumbles	2 mm maximum size	2.5, 5, 10, 15, 20, and 25	-
Tajdini et al., (2016)	Kaolinite	Crumbles	Two size ranges of 2- 5mm; and 1-3 mm	5, 10, and 15	-
Ajmera et al., (2017)	MH, CH, ML	Crumbles	Five sizes ranges of 4-16 mesh, 10-30 mesh, 30-50 mesh,	2, 4, 6, 8 and 10	-

			50-80 mesh, and 80-200 mesh		
Mukherjee and Mishra, (2017)	CH	Chips	4.75-2 mm	5, 10, and 15	Sand-90%

2.2.1 Effect of waste rubber tire inclusion on Atterberg's limits of fine-grained soils

Atterberg's limits or Consistency limits of fine-grained soil is defined as water content at which it changes its state from solid to semi-solid, plastic, and liquid state. The minimum amount water content at which soil offers negligible shearing resistance is called as the liquid limit. Whereas, the plastic limit is defined as water content at which soil just fails to behave plastically. The soil attains a semi-solid state below plastic limit. In semi-solid state, the decrease in water content does not influence the volume reduction of soil very appreciably. At shrinkage limit, soil stops shrinking and attain a constant volume. The swelling and shrinkage properties of fine-grained soil can be bitterly understanding by the values of shrinkage limit. The values of liquid limit and plastic limit are directly used for classifying fine-grained cohesive soil and help in understanding the behaviour of soil for selecting the suitable methods of design, construction and maintenance of structures made up and resting on soils. The values of shrinkage limit are used for calculating the shrinkage factors which helps in the design problems of structures formed of the soils and resting on soil. It gives an idea about the suitability of the soil as a construction material in foundations, roads, embankments, and dams. This section of the chapter reviews the impact of various forms of rubber tire wastes namely, shreds granulates (crumbles), fibres (buffings), chips, and ash on Atterberg's limits of soft/ weak soils.

Srivastava et al., (2014) evaluated the effect of fine (passing 2.00-0.075 mm retaining) and coarse (passing 4.75-2.00 mm retaining) size shredded tire on index properties of expansive soil. They mentioned that clay with 10%, 20%, 30%, 40%, and 50% fine and coarse shredded tires show 11.47%, 14.75%, 21.31%, 24.59%, and 31.14% and 1.63%, 8.19%, 18.03%, 24.59%, and 34.42% decrease in liquid limit, respectively. Results of plastic limit were in similar lines. The plasticity index of clay-coarse sized shredded tire was reported to remain constant up to 20% inclusion of coarse size shredded tires. For fine size shredded tire, the plasticity index remains almost unchanged. The decrease in quantity of clay with the inclusion of shredded tire was the reason behind decreased liquid limit and plastic limit as shown in Fig. 2.1. In the same study, Srivastava et al., (2014) reported that inclusion of 10%, 20%, and 30% fine and coarse sized shredded tire led to significant shrinkage limit improvement of 14.94%, 42.52%, and 60.91% and 47.12%, 74.71%, and 102.29%, respectively. The mixture with 10%, 20%, and 30% replacements showed the major shrinkage ratio loss of 10%, 25%, and 30% for fine size shredded tires and 20%, 30%, and 37.5% for coarse size shredded tires. The value of shrinkage ratio of expansive soil incorporated with coarse size shredded tire was reported to be lower as compared to that of fine size shredded tires. The reduction in mass-specific gravity of soil with the inclusion of shredded tire was the reason behind decreased shrinkage ratio. They concluded that inclusion of coarse size shredded tire in expansive soil was beneficial as it controls shrinkage more efficiently as compared to fine size shredded tire.



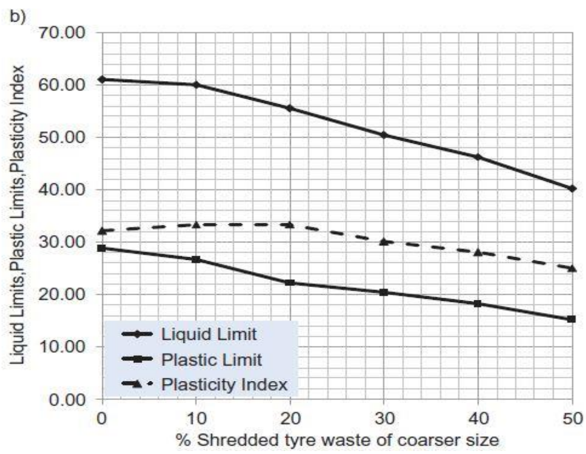


Fig. 2.1 (a) Change in liquid limit, plastic limit, plasticity index as % of shredded tyre waste of finer category increases, **(b)** Change in liquid limit, plastic limit, plasticity index as % of shredded tyre waste of coarser category increases (Srivastava et al. 2014)

Seda et al., (2007) evaluated index properties of expansive soil incorporated with 20% granulated rubber (by weight) of size smaller than 6.7 mm. An approximately negligible change in Atterberg's limits and plastic indices of expansive soil with the inclusion of rubber was reported because of less than 0.4% (by weight) waste tire particles was found smaller than 40 µm sieve.

Cetin et al., (2006) examined the effect of fine-grained (particle size below 0.425 mm) and coarse-grained (particle size between 2-4.75 mm) tire chips on Atterberg's limits of cohesive soil. Low plasticity clayey soil was partially replaced with tire chips at levels of 0%, 10%, 20%, 30%, 40%, and 50%, by weight. Atterberg's limits of clay decreased with increasing tire chip content. They observed that the incorporation of coarse tire chips (up to 30%) did not affect liquid limit of cohesive soil significantly. Further inclusion of tire chips decreased the liquid limit of mixture. The reduction in liquid limit was nearly 9.5% and 23.80%with the addition of 40% and 50% tire chips, respectively. Similarly, plastic limit of the clay containing coarse tire chips (up to 10%) was comparable to clay. Incorporation beyond 10% led to the reduction in plastic limit of clay. With the inclusion of 20%, 30%, 40%, and 50% coarse tire chips, the reduction in plastic limit was 12%, 16%, 24%, and 20%, respectively as shown in Fig. 2.2. The similar result was reported for incorporation of fine-grained tire chips in the cohesive soil.

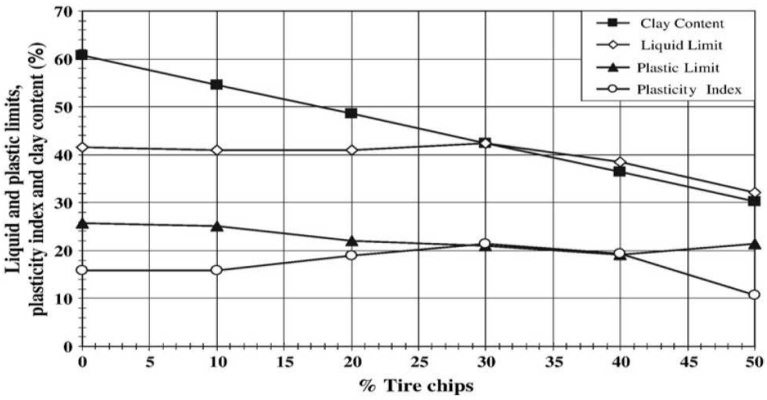


Fig. 2.2 Changes of liquid limit, plastic limit, plasticity index and clay content as the % tire-chips increases (Cetin et al. 2006)

Trouzine et al., (2012) scrutinized the influence of rubber fibres (average length of 7 mm) on consistency limit of clay of low and high plasticity. Rubber fibres at 0%, 10%, 20%, 25%, and 50% replaced the clayey soil, by weight. As the content of rubber fibres in clay increased, liquid limit of both the clay decreased gradually. The rate of decrement in liquid limit with the inclusion of rubber fibres was found more in high plasticity clay. The addition of rubber fibres beyond 10% led to gradual increment in plastic limit of both soils. The high plasticity clay was reported to be more susceptible to inclusion of fibres as compared to low plasticity clay because of its higher plasticity index.

From the review of literature, the effect of rubber tire wastes on Atterberg's limits of soil is not clear. Several investigators reported that inclusion of waste rubber tires in soil reduced the Atterberg's limits. On the contrary, few investigators believed that addition of rubber tire wastes to the soil increased Atterberg's limits. Still, more research is needed to confirm the impact of rubber tire wastes on the Atterberg's limits of soil.

2.2.2 Effect of waste rubber tire inclusion on compaction parameters of fine-grained soils

Compaction is the process of eviction of air from the voids of soil mass with aid of compactive energy to attain it densest state. The denseness of soil is measured in terms of its dry density. For a given compactive energy, soil attains the maximum dry density (MDD) at a particular moisture content, which is known as optimum moisture content (OMC). Compaction of soils increases their density, shear strength, bearing capacity but reduces their void ratio, porosity, permeability, and settlement. The results of compaction test are useful in the stability of field problems like earthen dams, embankments, roads, and airfields. This section reviews the effect of inclusion of various forms of rubber tire wastes namely, shreds, granulates (crumbles), fibres (buffings), chips, and ash on compaction characteristics of soft/ weak soils.

Al-Tabbaa et al., (1997) examined the effect of three different sizes of shredded tires on three different types of soil. Three different size ranges namely 1-4 mm, 4-8 mm, and 8-12 mm were used. A quantity of 6% shredded tire of size 1-4 mm, 15% shredded tire of size 4-8 mm, and 8-12mm was added to the kaolin, kaolin-lime and bentonite soils. The inclusion of shredded tire reduced the MDD of all types of soils. Whereas, OMC for each mixture of soil-tyre remained almost the same. In a similar study Al-Tabbaa and Aravinthan (1998) conducted compaction tests on clayey soil incorporated paraffin treated tire of two different sizes namely, 1-4 mm and 4-8 mm varying from 6 to 15% by weight. They had restricted the content of rubber up to 6-8% and 10-15% for 1-4 mm and 4-8 mm sizes keeping the leachability in view. They observed reduction in MDD as the content of rubber increased in the clay- tire mixtures. OMC of mixtures was observed to be unchanged by the increase in tire content. The low specific gravity of tire rubber was attributed as a reason for the decrease in density. Srivastava et al., (2014) mentioned that the MDD of expansive soil containing 5%, 10%, 20%, and 30% fine size (passing 2.00-0.075 mm retaining) and coarse size (passing 4.75-2.00 mm retaining) shredded tires, by weight decreases with rubber content. They reported higher amount of reduction in MDD of expansive soil with the inclusion of coarse size shredded tire as compared to the corresponding value of the MDD of expansive soil incorporated with fine size shredded tires.

Seda et al., (2007) evaluated the effect of inclusion of 20% granulated rubber (by weight) on compaction parameters of expansive soil. The inclusion of rubber led to reduction in maximum dry unit weight of the clay, attributed to the low specific gravity of rubber as compared to clay. No change in optimum moisture content of clay was accounted with the inclusion of rubber. Kim and Kang, (2011) used rubber (0.1 to 2 mm) in various percentages (0%, 25%, 50%, 75%, and 100%, by weight) in the RLS containing bottom ash (100%) and cement (20%). They stated that increasing the rubber content from 0% to 100% decreases the bulk unit weight of RLS samples from 15.1 kN/m^3 to 12.1 kN/m^3. The decreased bulk unit weight of RLS samples was attributed to the lower specific gravity of rubber compared to clay.

Priyadarshee et al., (2015) evaluated and compared the effect of inclusion of tire crumbles (4.75-0.150 mm size) on compaction parameters of fly ash and kaolin clay through standard Proctor test and modified Proctor test. The percentage inclusion of tire crumbles was 1%, 2%, 5%, 10%, and 20%, by weight. A consistent reduction in MDD of fly ash and kaolin was noticed as the content of tire crumbles increased. The loss in density was attributed to low specific gravity of tire crumbles. OMC of clay was reported to be increased with the addition of tire crumbles. The increase in water content was accredited to more water requirements of clay-tire crumbles mixtures to compact. They reported that the inclusion of tire crumbles does not significantly affect the OMC of fly ash. The maximum dry density of mixtures increased with increasing the compaction effort. At higher rubber content, the effect of compaction efforts on MDD was reported to be insignificant due to the flexibility of tire crumbles.

Signes et al., (2016) conducted standard and modified Proctor tests on the clay soil incorporated with different percentage (0%, 2.5%, 5%, 10%, 15%, 20%, and 25%, by the weight of dry soil) of crumb rubber (maximum particle size of 2 mm). As the percentage of crumb rubber in soil increased, MDD and OMC decreased. The decrease in maximum dry unit weight of the mixes was attributed to the low specific gravity of rubber particles. The decrease in OMC was accredited to lower water absorption capacity of crumb rubber. Ajmera et al., (2017) investigated the viability of utilizing crumb rubber in cohesive soil. Five types of soil (i) kaolinite (MH), (ii) montmorillonite (CH), (iii) granular kaolin (ML), (iv) 50% montmorillonite with 50% granular kaolin (CH), (v) 50% montmorillonite with 50% quartz (CH) was amended with crumb rubber of different sizes (6-14, 10-30, 30-50, 50-80, and 80-200 mesh) at levels of 0%, 2%, 4%, 6%, 8%, and 10% by weight. The impact of different sizes and quantum of crumb rubber on compaction parameters of the soils was studied by using Harvard miniature compaction apparatus. The increment in MDD of high plasticity silt was found with increasing the size and percentage of crumb rubber. The effect of size and content of crumb rubber was reported to be insignificant on OMC of high plasticity silt. On the other hand, a similar trend of increment in the MDD was found with the addition of crumb rubber of different sizes in clayey soil. They reported increment in MDD of clay with the addition of 2%-4% crumb rubber. Contrary to the silty soil, OMC of clayey soil was found to increase with the size of crumb rubber.

Cetin et al., (2006) examined the compaction characteristics of clayey soil incorporated with fine-grained (particle size below 0.425 mm) and coarse-grained (particle size between 2 - 4.75 mm) tire chips at levels of 0%, 10%, 20%, 30%, 40%, and 50%, by weight. The decrease in MDD was observed when coarse-grained and fine-grained tire chips replaced the clay. The reduction in density of clay with the incorporation of fine-grained tire chips was found to be more than coarse- grained tire chips. Besides, an increment in OMC was noticed in the case of fine-grained tire chips. Whereas contrary results were obtained with the incorporation of coarse- grained tire chips. They documented that the reduction in unit weight of mixtures with the addition of tire chips made the composite a potential candidate for lightweight fill materials.

Chan, (2012) documented a slight decrease in density with the increase in content of rubber in uncemented/cemented clayey sand. The addition of 1% rubber chips or shreds lowered the density of uncemented specimen by 1.04%, and 2.4% cemented specimen by 1.54%. The reduction in density was accredited to the low specific gravity of rubber chips/shreds. Mukherjee and Mishra, (2017)conducted standard proctor compaction test on the mixture of sand (90%, by weight) and Bentonite (10%, by weight) containing 5%, 10%, and 15% tire chips falling between 2 to 4.75 mm. The reduction in MDD from 1.76 g/cm^3 to 1.74, 1.71, and 1.69 gm/cm^3 was reported with increasing the percentage of tyre chip from 0% to 5%, 10%, and 15%, respectively. Reduction in maximum dry density was attributed to low specific gravity of tyre chips. OMC of mixture was found to be marginally affected with the inclusion of tyre chips.

Özkul and Baykal, (2006) studied the effect of standard and modified compaction effort on the clay included with 10% tire buffing. Tire buffings of 4 to 15mm length having the diameter between 0.3 to 1.5 mm were used in this investigation. The inclusion of tire buffings (10%) reduced the maximum dry unit weight of the clay, and this was accredited to the low specific gravity of tire buffings. The maximum unit weight of clay - tire buffings composite was recorded as 15.5 kN/m^3 and 15.7 kN/m^3 for the standard and modified compaction energies. They reported that the unit weight of mixture was not significantly influenced by the change of compaction efforts. The decrement in saturation level of clay-tire buffing composites was observed with the reduction of compaction energy. They reported that efficiency of modified compaction effort was significantly affected by incorporation of tire buffings in clayey soil as compared to that of standard compaction effort. Jafari and Esna-ashari, (2012) evaluated the effect of waste tire cord (nylon fibres) of 20 mm length and lime on compaction characteristics of low plasticity clay. The waste tire cord contents of 0%, 0.5%, 1%, and 1.5% and lime contents of 0%, 4%, and 8% by weight was incorporated in the soil. It was observed that inclusion of lime reduced the maximum dry unit weight and enhanced the optimum moisture content of the clay. The low specific gravity of lime and formation of voids due to Base Exchange and flocculation phenomena might have led to decrement in maximum dry unit weight of soil. The additional water required to fill the voids of the mixture was attributed as a reason behind the increase in OMC. The addition of waste tire cords reduced the maximum dry unit weight and optimum moisture content of clay-lime mixture due to low specific gravity and water absorption of fibres.

Kalkan, (2013) examined the compaction parameters of clay of high plasticity containing silica fume and rubber fibres. The percentage replacements for silica fume were 10% and 20% by weight. Rubber fibre of 5 to 10 mm length having thickness 0.25 mm to 0.50 mm varying from 1% to 4% in step of 1% was used. They reported that the inclusion of rubber fibres decreased the maximum dry unit weight and OMC of the clay-silica fume mixtures as demonstrated in Fig. 2.3. The decrease in unit weight due to the inclusion of silica fume and rubber fibres was accredited to the fineness of silica fume, which occupied the voids of mixtures and low specific gravity of the rubber fibres. Inclusion of silica fumes enhanced the OMC of mixes. OMC of clay containing 10% silica fume reduced progressively from 0.74% to 2.96% with increasing the rubber content from 1% to 4%, respectively. The large specific surface area of silica fume might have led to increased OMC, whereas the change in gradation with rubber fibres inclusion might have led to decreased OMC of the mixes. Cabalar et al., (2014) evaluated the compaction parameter of clay incorporated with 2%, 4%, and 6% lime and 5%, 10%, and 15% tyre buffing ranging between 0.6 and 4.75 mm. The soil with 5%, 10%, and 15% tyre buffing (by weight) recorded 5.25%, 11.35%, and 15.19% and 5%, 10%, and 15% reduction in maximum dry unit weight and OMC, respectively. They reported that low specific gravity and low water absorption capacity of tyre buffing might have led to reduced maximum dry unit weight and OMC. The maximum dry unit weight of rubberized clay further reduced when lime was incorporated. OMC was observed to be increased with the inclusion of 2%, 4%, and 6% lime content in rubberized clay. The enhancement in OMC of mixes could be because of the requirement of water for hydration reaction of lime and high water absorption capacity of lime.

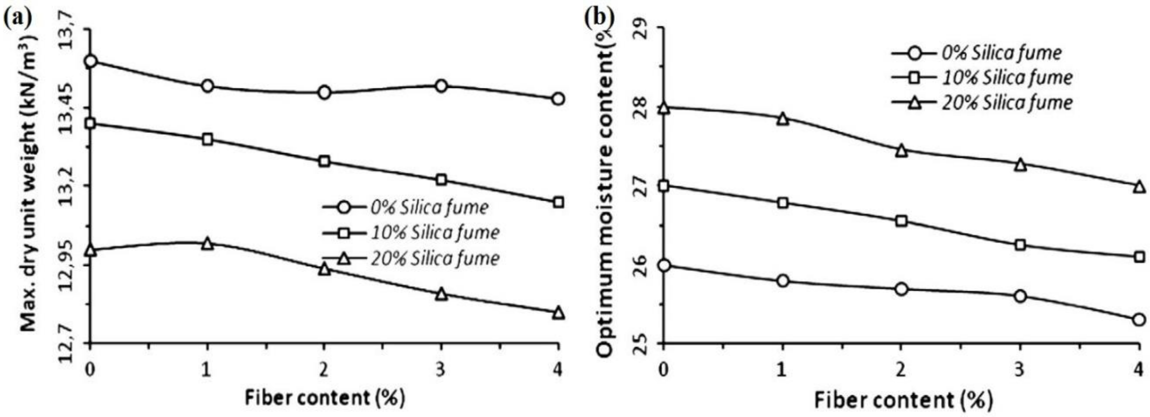


Fig. 2.3 Effect of the scrap tire rubber fibre on the **(a)** maximum dry unit weight; **(b)** OMC (Kalkan 2013)

The majority of published research articles show that rubberization of soil lead to a decrease in maximum dry unit weight. From the review of literature, the effect of rubber tire wastes on optimum moisture content of soil is not clear. Several investigators reported decrement while some researchers documented increment in optimum moisture content of soil incorporated with rubber tire wastes. Other even observed no change in optimum moisture content. Still, more investigation is needed to confirm the effect of rubber tire wastes on compaction parameters of soil, particularly optimum moisture content.

2.2.3Effect of waste rubber tire inclusion on shear strength of fine-grained soils

Shear strength of the soil is defined as the maximum resistance offered by the soil against shearing stress at failure on the failure plane. It composes two parameters (i) internal friction and (ii) cohesion. Internal friction is defined as a resistance between the individual particles of soil at their contact points due to friction. Whereas, cohesion is resistance due to inter-particles forces, which tend to hold the particles together in a soil mass. The strength parameters, namely the cohesion and angle of shearing resistance are determined in the laboratory by unconfined compression test, direct shear test, vane shear test, and triaxial compression test. Shear parameters are used in (i) the design of earthen dams and embankments, (ii) calculating the bearing capacity of soil-foundation systems, and (iii) estimating the earth pressures behind the retaining walls. This section of the chapter reviews the effect of inclusion of various forms of rubber tire wastes namely, shreds, granulates (crumbles), fibres (buffings), chips, and ash on shear strength characteristics of soft/ weak soils.

Al-Tabbaa et al., (1997) investigated the unconfined compressive strength of kaolin, kaolin-lime and bentonite soils containing shredded tyre of 1-4 mm, 4-8 mm, and 8-12 mm sizes. They observed that the unconfined compressive strength decreased with the increase in shredded tyre content. At 10% tyre content, the unconfined compressive strength of soil-tyre mixture remained same for all three-tyre sizes. The trend observed for the reduction in unconfined compressive strength of kaolin-tyre and bentonite-tyre was similar, but a steep drop in the unconfined compressive strength was noticed for kaolin-lime-trye mixtures. This steep drop in strength was attributed to poor bonding between the kaolin-lime mixture and tyres particles. In a similar study, Al-Tabbaa and Aravinthan, (1998) evaluated the unconfined compressive strength of clayey soil incorporated with paraffin treated rubber tire of 1-4 mm and 4-8 mm sizes varying from 6-8% and 10-15%, by weight, respectively. They observed that the addition of rubber tires reduced the strength by 40% approximately. This was attributed to the angular shape of tire particles. The inclusion of rubber tire led to reduction of stiffness of the clay. The failure strain corresponding to peak stress of the mixtures was found to be approximately similar to that of clay but prolonged strain range almost twice that of clay alone.

Srivastava et al., (2014) explored the effect of fine size (passing 2.00-0.075 mm retaining) and coarse size (passing 4.75-2.00 mm retaining) shredded tires varying in different proportions (5%, 10%, 15%, and 20%, by weight) on the unconfined compressive strength of expansive soil. The inclusion of 5% coarse size shredded tire improved the undrained cohesion value of clay by approximately 60%. Incorporations beyond 5% led to significant undrained cohesion reduction as demonstrated in Fig. 2.4. The undrained cohesion value of expansive soil containing coarse sized shredded tire was reported to be higher than the corresponding value of undrained cohesion value to expansive soil-fine sized shredded tire mixtures.

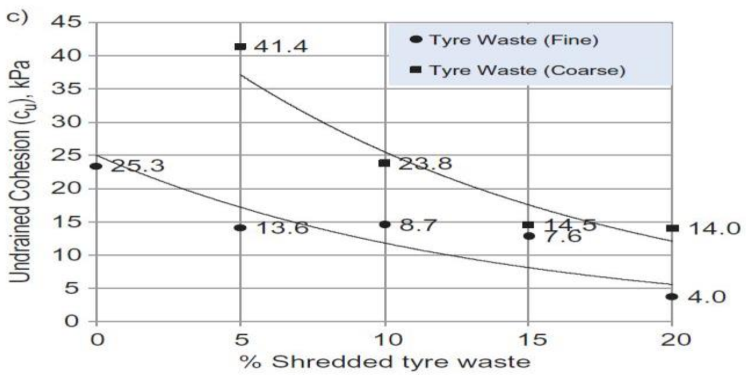


Fig. 2.4 Undrained cohesion (cu) values of black cotton soil partially replaced with shredded tyre waste of coarse and fine categories. (Srivastava et al. 2014)

Cokca and Yilmaz, (2004) assessed the impact of granulated rubber (850 µm to 75 µm) and bentonite on unconfined compressive strength of fly ash specimens cured for 3 and 7 days. The content of fly ash in mixtures was kept constant (i.e. 90%) and replacement levels for rubber was taken as 0%, 1%, 3%, 5%, 7%, 9%, and 10%, by dry weight of the mixtures and bentonite was taken as 10%, 9%, 7%, 5%, 3%, 1%, and 0%, by dry weight of the mixtures. They observed that the unconfined compressive strength of the mixtures decreased with the increase in rubber content from 0 to 10% and the drop in bentonite content from 10% to 0. For 7 days cured specimens of mixtures, an increase of 10-30 times in unconfined compressive strength were observed when compared to the compacted specimens. No significant improvement in the strength of the mixtures was reported with the prolongation of curing time from 7 days to 28 days. They mentioned reduction in secant modulus of mixtures when the rubber content increased from 0 to 10% and bentonite decreased from 10% to 0, respectively. The low secant young's modulus of rubber might be the reason behind decrement in secant modulus of mixtures. At higher rubber content (7%, 9%, and 10%), a significant increase in the axial strain corresponding to peak axial stress of the mixtures was witnessed. An increment in plastic energy capacities and decrement in elastic energy capacities were also reported with the inclusion of rubber in mixtures and were attributed to the low elastic modulus of rubber, which led to the reduction in the elastic energy capacities of the mixes.

Kim and Kang, (2011)examined the effect of rubber of stress-strain response of RLS samples containing bottom ash (100%) and cement (20%). Rubber particle of the size between 0.1 to 2 mm varying from 0% to 100% in step of 25% was used in this investigation.

They mentioned a reduction in unconfined compressive strength of RLS specimens from 440 kPa to 180 kPa when the content of rubber increased from 0% to 100%. The decrease in strength was accredited to loss of friction and bonding in the matrix. Whereas, the axial strain corresponding to peak axial stress was observed to be increased with rubber content. They found that the axial strain of RLS specimens increased from 2% to 3.7% approximately when the rubber content was increased from 0% to 100%. The increased axial strain was attributed to the rubber-like behaviour of RLS specimens at higher rubber content, which may lead to behaviour that is more ductile. RLS specimens containing 0 to 25% rubber demonstrated higher shear modulus. They documented that inclusion of higher rubber content (50-100%) increased the shear modulus. The increased shear modulus was credited to compressibility and rubber-like response with the addition of higher rubber content.

Wang and Song, (2015) investigated the compressive strength of low plasticity clay mixed with ordinary Portland cement and two sizes of crumb rubber on the cubical specimens of size 70.7 mm. The clay was partially replaced cement at the level of 7%, 15%, 20%, and 25%, by weight and crumb rubber (30/40 and 60/80 mesh) varying from 0 to 20% in a step of 5% by the weight of cement was incorporated as a replacement of cement. The results showed a decrease in compressive strength of cement stabilized clay with increasing crumb rubber content. The decline in 28 days' compressive strength of clay stabilized with 20% cement was 4%, 10%, 14%, and 17% with the inclusion of 5%, 10%, 15%, and 20% crumb rubber of size 30/40 mesh, whilst the decrease in 90 days' compressive strength was 14%, 14%, 25%, and 31%, respectively. They reported that the size of crumb rubber particles does not significantly affect the compressive strength of mixes. It was observed that the peak strain corresponding to peak axial stress increased with increasing the rubber content. The improvement in plasticity of cemented clayey soil incorporated with 60/80 mesh crumb rubber was found better than the same incorporated with 30/40 mesh crumb rubber.

Tajdini et al., (2016) evaluated the shear strength of Kaolinite clayey soil added with crumb rubber (G30 and G80, G30 coarser and uniformly graded than G80) through a series of triaxial tests conducted in consolidation drained (CD) and unconsoildation undrained conditions (UU). The clayey soil was partially substituted with crumb rubber in steps of 0%, 5%, 10% and 15%, by weight, respectively. It was observed that the peak shear stress of clayey soil incorporated with 10% crumb rubber (G30) was lower in UU condition as compared to CD condition. The reduction in peak shear stress was approximately 78% with the inclusion of 5%, 10%, and 15% crumb rubber at confining stresses of 100, 200, and 300 kPa. They reported that the specimens show dilation behaviour in CD condition after an initial settlement, whereas insignificant dilation was observed in the specimens in UU condition. The ductility of mix increased with increasing the confining stress. It was observed that failure of unreinforced specimens occurs at an angle of 45^0 with the horizontal (i.e. angle at which shear stress dominates), which was an indication of brittle behaviour. The failure of reinforced specimen was found to occur at an angle closure to the horizontal axis, which led to improvement in ductility of the mix. They reported a noticeable increase in friction of clay with the inclusion of crumb rubber content up to 10% as illustrated in Fig. 2.5(a). The increment in crumb rubber content also led to decrease in cohesion value of the mixture as manifested in Fig. 2.5(b). The dilation angle and shear stiffness of mixture in drained condition were reported to be higher than the mixture in undrained condition. A reduction in elastic modulus with the increase in content and size of crumb rubber in the mixture was observed. The higher strength and friction angle of mixture containing G30 crumb rubber particles as compared to G80 particles were reported because of the better interaction of G30 (coarse size) particles with clay particles. The reduction in cohesion value of clay with the addition of crumb rubber was attributed to the decline in dominancy of the electromagnetic force between clay particles, which led to the separation of clay particles as the content of crumb rubber increases.

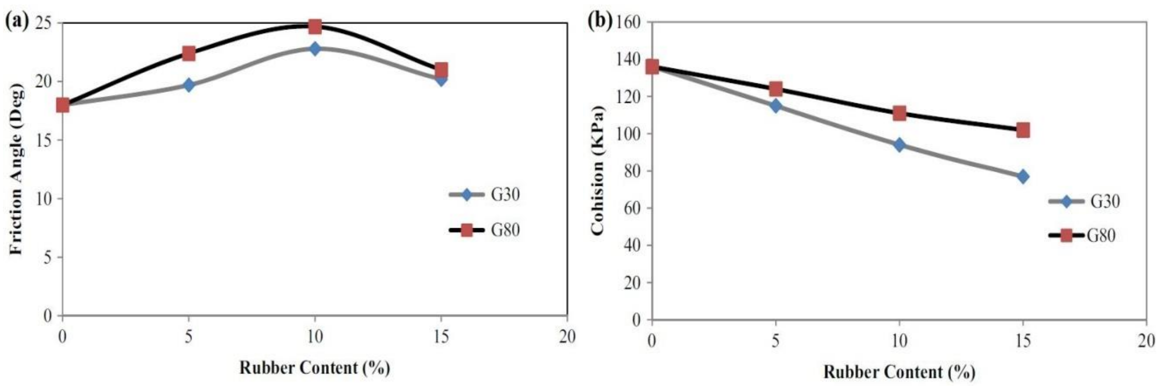


Fig. 2.5(a) Variation of the internal angle of friction with crumb rubber Content **(b)** variation of the cohesion with crumb rubber content(Tajdini et al. 2016)

Signes et al., (2016)evaluated the drained shear strength of clay-rubber mixtures. Crumb rubber (maximum size of 2 mm) was incorporated at levels of 0%, 2.5%, 5%, 10%, 15%, 20%, and 25%, by weight. Results showed a linear increment in the effective friction angle of clayey soil with the addition of crumb rubber. The increase in friction angle was accredited to the higher friction between rubber particles as compared to soil particles. In the same study, Signes et al., (2016) evaluated the unconfined compressive strength of clay – crumb rubber mixtures at different contents of rubber. They reported a reduction in unconfined compressive strength of clay with the addition of rubber particles, while the axial strain corresponding to the peak stress increases. They documented that the higher content of rubber particles flattens the peaks corresponding to failure. Ajmera et al., (2017)investigated the effect of varying sizes and percentage of crumb rubber on unconfined compressive strength of high plasticity silty and clayey soils. They reported maximum unconfined compressive strength of silty soils incorporated with 2-4% crumb rubber. Whereas, the inclusion of 4% crumb rubber gave maximum unconfined compressive strength for clayey soil. They observed the brittle behaviour of kaolin clay specimens incorporated with 4% (50-80 mesh) shredded rubber tire prepared at dry side of optimum from stress-strain response. The ductile behaviour was noticed for the specimens prepared at water content greater than optimum. The addition of rubber tires up to 6% increased the unconfined compressive strength of kaolin clay, regardless of size of the tire. In general, they reported the unconfined compressive strength of clay increased with the decrement in size of waste.

Ho et al., (2011)scrutinized the effect of rubber chips (average size 2 to 5 mm) and cement on unconfined compressive strength of kaolin clay. The percentage of rubber chips and cement used in the investigation were 5%, 10%, and 15% and 2% and 4% (by weight) respectively. They reported that the unconfined compressive strength of clay containing rubber chips increased with increasing the content of cement, while it reduced with enhancing the percentages of rubber chip in the mixtures. The increase in strength with the inclusion of cement was attributed to hydration reaction of cement.

Chan, (2012)evaluated the effect of rubber chips/shreds on unconfined compressive strength of clayey sand stabilized with 2 to 4% cement. She reported that unrubberized cemented clayey sand specimen showed higher peak strength at low strain, which was indicative of brittleness, high stiffness, and no post-peak strength. The inclusion of rubber provided some post failure resistance to cement stabilized clayey sand because of the crack-resisting ability of rubber component in the mix. She suggested that at higher cement content, the ductility provided by inclusion of rubber in the mix was affected and residual strength of mix was found to be reduced. The increasing percentage of rubber in clayey sand containing the same amount of content shows a reduction in peak strength, higher the failure strain corresponding to peak strength, lower the stiffness and young modulus of the mix. It indicated that up to a certain extent, the inclusion of rubber enhanced the ductility and prevented brittle failure of cement stabilized clayey sand.

Mukherjee and Mishra, (2017)evaluated the effect of inclusion of 5%, 10%, and 15% tyre chips (passing 4.75 mm and retaining on 2 mm) on the shear strength of sand –bentonite mixture (90% sand and 10% bentonite) through unconfined compressive strength and undrained triaxial tests. They reported a consistent improvement in unconfined compressive strength of the mixture with increasing the percentage of tyre chips. The high interfacial friction between tyre chips and mixture might be attributed as a reason for such observations. A continuous increase in failure strain was observed with increasing the percentage of tyre chips. The increment in failure strain was accredited to compressible tyre-to-tyre interaction. The results of triaxial test reported by the authors revealed gradual improvement in friction angle of the mixture with the inclusion of tyre chips. Whereas cohesion of the mixture was reported to be increased up to 10% incorporation of tyre chips, beyond that it decreased. The reinforcement effect of tyre chips increased the failure strain of mixture containing 10% tyre chips from 8.2% and 9.0% to 8.8% and 9.7% under confining pressure of 50 and 150 kPa, respectively. This was attributed to compressible tyre- to-tyre interaction in the mixture. They reported that the addition of tyre chips lowered post-peak drop of strength and decreased the peak pore water pressure ratio as well. The prevention of formation of the shear bond due to deformation and starching of tyre chips that restricted the movement of particle might have led to such results. It was concluded that inclusion of tyre chips changed the catastrophic behaviour of sand-bentonite mixture to ductile.

Özkul and Baykal, (2006) evaluated the shear strength of kaolinite clay of low plasticity incorporated with 10% tire buffing (4 to 15 mm length) in both drained and undrained conditions. The specimens of tests were prepared at standard and modified compaction energies. The results of undrained unconsolidated test revealed that by employment of standard compactive effort, the peak strength of clay-rubber matrix was decreased slightly as compared to clay. At modified compactive effort, the strain required to attain the peak strength of rubberized clay matrix was observed to be more than unrubberized soil. The increased unit weight and strength were accredited as a reason for such behavior. The strength of rubberized clay was reported to be slightly lower than clay in consolidated drained conditions at both energy levels. From this study, they suggested an effective friction angle of 33^0 that could be used for the design of earth structures made up of rubberized clay and clay alone. In an identical study, Özkul and Baykal, (2007)evaluated the shear strength of kaolinite-rich clay incorporated with 10% rubber fibers through consolidation drained and consolidation undrained triaxial tests conducted at 50 kPa to 300 kPa confining stress. The specimens were prepared at modified and standard compaction energies. They observed slightly higher peak strength of composite as compared to clay at all confining pressures (except 300 kPa). The development of strength occurred more slowly for rubberized clay as compared to unrubberized clay. The clay-rubber mixture showed a significant amount of initial contraction spread over a wider range of strain. The disparities in water content of the composite and compression of rubber fibres were attributed as the reason for such an observation. They reported a greater loss of post-peak strength of clay-rubber matrix tested at 300 kPa confining pressure. An increment in cohesion value of rubberized clay from 34 kPa to 64 kPa was observed as compared to unrubberized clay. However, an opposite trend was reported for change in friction angle. It was found that friction angle of clay decreased from 29.3^0 to 27.6^0 as compared to rubberized clay. They documented that the peak strength and pore water pressure of rubberized clay at standard compactive effort in consolidation-undrained conditions were higher than unrubberized clay at all confining pressures. A barreling type of failure was observed in the specimens of rubberized clay.

Akbulut et al., (2007) demonstrated the effects of length and content of rubber fibres on unconfined compressive strength of three clayey soil of high plasticity. Three different lengths of rubber fibres ranging between 2 to 5 mm, 5 to10 mm, and 10 to 15 mm in varying percentages of 1%, 2%, 3%, 4%, and 5%, respectively was used. They reported the maximum unconfined compressive strength of soils containing 2% rubber fibre content of length 10 mm. The unconfined compressive strength of clayey soil specimens was found out to be maximum for 2% inclusion of rubber fibres of 10 mm length. The incorporations beyond 2% led to decrease in strength but found more than unreinforced soil specimens. In the same study, Akbulut et al., (2007) reported the results of direct shear test to assess the impact of various proportions and length of rubber fibres on cohesion and fiction angle of three types of clayey soil of high plasticity. It was documented that the highest increment in cohesion of cohesive soil occurred at 2% inclusion of rubber fibres of 10 mm length as compared to the other proportions and lengths. Likewise, the friction angle of soil containing rubber fibres of length 5 mm was found more than other lengths. The tension produced in fibres due to the enhancement of confining pressure might have led to increasing in cohesion along with the layer of absorbed water formed on clay particles due to the moisture content of fibre enabled the soil-fibre mass to perform as the coherent matrix, which resulted in such observations.

Jafari and Esna-ashari, (2012) examined the unconfined compressive strength of clayey soil with 0.5%, 1%, and 1.5% containing tire cord waste of 20 mm length and 4% and 8% lime content. The result of specimens obtained from non-freeze-thaw conditions showed that the unconfined compressive strength of the clay containing 0% lime exhibited increment with increasing the percentage of tire cord as compared to the clay and maximum unconfined compressive strength was found with the addition of 1.5%. Beyond 1.5% inclusion, reduction in strength was found. At higher fibre content (>1.5%), the decrease in strength was attributed to the agglomeration of fibres which led to the reduction of effective interfacial contact area between fibers and clay. The inclusion of lime increased the strength of fiber-reinforced clay. They reported that addition of 4% lime increased the strength more as compared to the inclusion of 8% lime in the same mixture. This was attributed to the presence of free lime in stabilized clay, which acted as non-cohesive material in the clay. It was found that addition of fibres increased the failure strain of unstabilized clay slightly, but the initial stiffness of specimens remained the same. Incorporation of lime reduced the strain at failure, residual strength and enhanced the initial stiffness of the clay. They observed that the addition of fibres remediates the problem created by the inclusion of lime in clay up to certain extent and changed the behavior of composite from brittle to ductile.

Kalkan, (2013) analyzed the unconfined compressive strength of clay containing silica fume (10% and 20%, by weight) and varying proportions rubber fibres of 5 to 10 mm length (0 to 4%, by weight). It was found that the clay containing 20% silica fume exhibited maximum increment in unconfined compressive strength. The calcium silicate hydrate gel formed by reaction between active silica fume and Ca^{2+} and OH- ions of clayey soils caused this increase in strength but made the mix more brittle. The unconfined compressive strength of mixture increased further with the increase in content of rubber fibres up to 2%. Inclusion beyond 2% led to the reduction of strength. The improved strengths were accredited to skin friction developed between clay-silica fume mixture and surface of fibres. Increased friction led to the dissipation of big cracks and formation of the small crack in specimens of clay containing 20% silica fume, and 2% was observed. In the same study, Kalkan, (2013) evaluated the cohesion value and angle of internal friction of clay modified with silica fume and rubber fibres through the direct shear test. The inclusion of silica fume improved the cohesion and friction angle of clay. For 10% and 20% addition of silica fume, an improvement of 5.55% and 9.44% was reported for cohesion value and an increment of friction angle from 15^{o} to 23^{o} and 28^{o} was found. The maximum cohesion value and friction angle were obtained for the mix containing 20% silica fume and 2% rubber fibres. The increase of 34.51% and 20^{o} in cohesion value and friction angle was observed with the inclusion of 2% rubber fibres in clay containing 20% silica fume. Further inclusion of rubber fibres beyond 2% led to decrease in cohesion value and friction angle. Reason cited for the increase in strength parameter were (i) internal friction between particles of silica fume; (ii) formulation of hydration products from reaction between clay particles and silica fume particles; (iii) tension developed in the fibres due to increase in confining pressure; (iv) absorbed water of fibres enabled the mixture to act as single coherent matrix.

Cabalar et al., (2014) assessed the impact of tyre buffing (5%, 10%, and 15%, by weight) and lime (2%, 4%, and 6%) content on unconfined compressive strength of the clayey soil. The specimens of clay + tyre buffing + lime were prepared at (i) optimum water content; (ii) optimum water content- 4% (dry side); (iii) optimum water content + 4% (wet side). Clay mixes with 5%, 10%, and 15% tyre buffings recorded 26.33%, 58.53%, and 69.63% reduction in unconfined compressive strength as compared to the clay. The maximum value of strength for rubberized clay at dry side of optimum was found out to be corresponding to 4% lime content. While it was found highest when 6% lime content was incorporated at the wet side of optimum water content. At dry side, the quantity of water was not sufficient to hydrate all lime in specimen, and some lime acted as a filler was interpreted as the reason for such a response. On the other hand, at wet side, the quantity of water was enough to hydrate all the lime in the specimens. Otoko and Pedro, (2014) examined the unconfined compressive strength of two clay namely; Chikoko soil (CH) and Laterite soil (CI) stabilized with 2% and 4% cement and incorporated with 5%, 10%, and 15% rubber fibres of 10 to 20 mm length. The unconfined compressive strength of cement-stabilized soils was found out to be maximum for 5% inclusion of rubber fibres at all ages of curing. Incorporation beyond 5% led to decrease in unconfined compressive strength.

From the above literature, it can be noted that inclusion of rubber tire waste reduced the unconfined compressive strength of fine-grained soil as reported by many investigators. On the contrary, few investigators believed that the addition of waste rubber tires to optimum percentage increased the strength. From the results reported by majority of the researchers, it can be established that the incorporation of rubber tires up to optimum percentage increases the cohesion and friction angle of the soil. In Few cases, the reduction in cohesion and friction angle has also been seen. Therefore, there is a need to carefully investigate the effect of incorporating rubber tire wastes with fine-grained soil on shear strength parameters of the mixture. Studies about the combined effect of cement/lime and rubber tire wastes on strength parameters of fine-grained soil are also scarce.

2.2.4 Effect of waste rubber tire inclusion on tensile strength of fine-grained soils

The tensile stresses are induced in earth structures due to the movement of vehicles, reduction in volume due to shrinkage, alternate drying and wetting of soils, thermal stresses due to seasonal variation in temperature. For determination of tensile strength of soils various tests like direct tensile test, split-cylinder test (split tensile strength test), bending test, and double punch tensile test are used. This section of chapter reviews the effect of inclusion of various forms of rubber tire wastes namely, shreds, granulates (crumbles), fibres (buffings), chips, and ash on tensile strength of soft/ weak soils.

Cokca and Yilmaz, (2004) evaluated the performance of fly ash-bentonite-rubber mixtures under tensile load through split tensile strength tests. Seven mixtures containing 90% fly ash were prepared by inclusion of 0%, 1%, 3%, 5%, 7%, 9%, and 10% granulated rubber of size ranged between 75 -850 µm and 10%, 9%, 7%, 5%, 3%, 1%, and 0% bentonite, respectively. They observed reduction in split tensile strength of the mixtures with the increase in content of rubber and decrease in percentage of bentonite. They reported that as rubber increases and bentonite decreases, the secant Young's modulus decreases. The decrease in secant Young's modulus was because of the rubber, since rubber particles have very low secant Young's modulus. The brittle behaviour was observed for the specimens incorporated with 1%, 3%, and 5% rubber. The inclusion of 7%, 9% and 10% rubber content changed it to ductile. The detention in widening of the crack due to springs like the behaviour of rubber particles helped the specimens to bear load even after failure and increased the strain taking ability of specimens might have led to such results.

Studies about the impact of rubber tire wastes incorporation on tensile strength of soil are scarce. From limited available literature, it can be noted that inclusion of rubber tire wastes in soil reduced the tensile strength. Future research addressing the impact of rubber tire wastes addition on tensile and flexural strength of soil stabilized with cement/lime is still needed.

2.2.5 Effect of waste rubber tire inclusion on consolidation characteristics of fine-grained soils

The process that involves a slow escape of water and a gradual pressure adjustment between the soil grains simultaneously is termed as ‘consolidation’. The main aim of consolidation test is to obtain soil data that are used in predicting the rate and amount of settlement of structure founded on clay primarily due to the volume change of the clay. This section of chapter reviews the effect of inclusion of various forms of rubber tire wastes namely, shreds, granulates (crumbles), fibres (buffings), chips, and ash of rubber tire wastes on the consolidation characteristics of soft/ weak soils.

Srivastava et al., (2014) studied the consolidation characteristics of expansive soil partially substituted with 10%, 20%, and 30% shredded tyres of two sizes (coarse size ranging from 4.75-2.00 mm and fine size ranging between 2.00-0.075 mm). It was observed that the values of compression index increased by 3.4%, 8.65%, and 24.91%, with the increase in percentage of coarse size shredded tyres from 10%, 20%, and 30% respectively. Similarly, at 10%, 20%, and 30% fine size shredded tyres, the improvement of 7.95%, 12.8%, and 33.91% in compression index was observed as shown in Fig. 2.6(a). A similar effect of shredded tyres inclusion on the coefficient of consolidation was observed as demonstrated in Fig. 2.6(b). The increment in coefficient of permeability with the addition of shredded tire was attributed as reason behind the increase in consolidation properties.Seda et al., (2007) scrutinized the influence of 20% rubber (< 6.7 mm size) inclusion (by weight) on compression and recompression indices and swell percent of expansive soil. The addition of rubber increased the compression and recompression indices of expansive soil by 23.80% and 57.14%, respectively. Whereas swell percentage reduced by 48.78%.

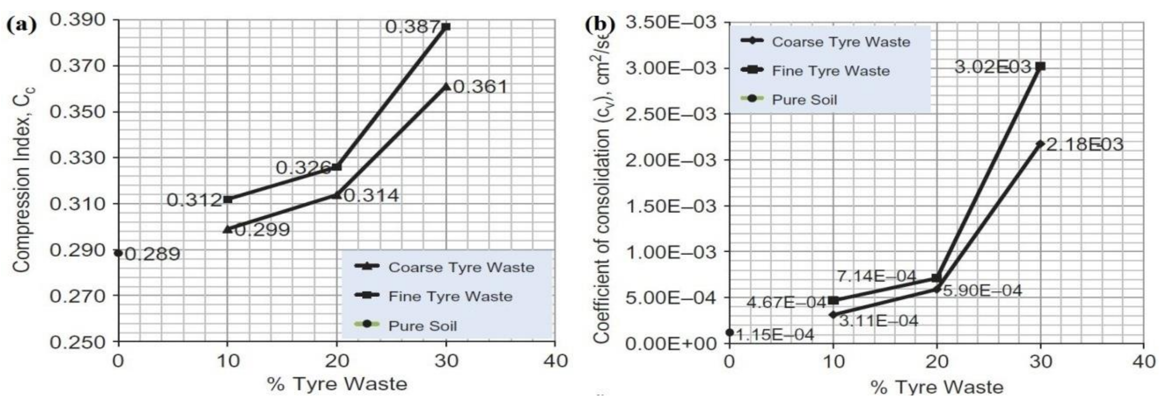


Fig. 2.6 (a) Compression index (C_C), **(b)** Coefficient of consolidation of black cotton partially replaced with shredded tyre waste of coarse and fine categories (Srivastava et al. 2014)

Cokca and Yilmaz, (2004) conducted the study on compressibility parameters of fly ash bentonite -rubber mixtures. The specimens of fly ash amended with 0 to 10% rubber and 10% to 0 bentonite recorded increment in coefficient of volume change with the increase in rubber content and the decrease in percentage of bentonite. Signes et al., (2016)explored the effect of crumb rubber on the compressibility of clayey soil. Samples were prepared with 0%, 2.5%, 5%, 10%, 15%, 20%, and 25% clay replacement by crumb rubber of maximum 2 mm particle size. They demonstrated that clay containing crumb rubber could have similar compression index to that of clay. The inclusion of crumb rubber increased the swelling index of clayey soil. The increment in swelling index was approximately 40% with inclusion of more than 20% crumb rubber as manifested in Fig. 2.7.

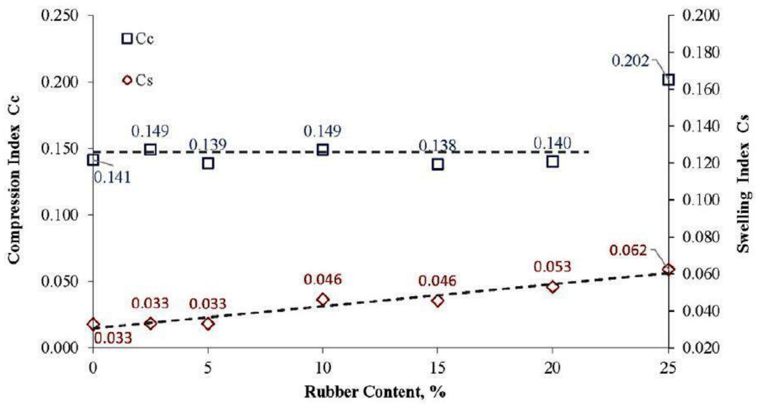


Fig. 2.7 Geotechnical test: unidimensional consolidation of tests (compressive index, C_C, and swelling index, C_S, vs rubber content) (Signes et al. 2016)

Ho et al., (2010) advocated the effect of rubber chips (2 to 5 mm average size) on compressibility characteristics of cement treated Kaolin clay at vertical stress levels of 12.5 kPa, 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, and 800 kPa. Rubber chips and cement were incorporated in the percentage of 0-15% and 0-4% by weight, respectively. They reported that the quantity of rubber chips controls the stiffness of clay. The inclusion of rubber (up to 10%) does not improve the stiffness of soil. Beyond 10% incorporation, the stiffness of clay increased significantly. The inclusion of cement reduced the compressibility of clay and increased the yield stress of mixtures because of cation exchange reaction, which led to the formation of hydration products. A decrement in yield stress of mixtures containing cement and 15% tire chips was observed. The high amount of tire chips turned the mixtures into granular material and gave sufficient stiffness than cementation was attributed as reasons for such observations. A declining trend in compression and recompression indices was observed with the increase of rubber and cement content in the mixtures.

Mukherjee and Mishra, (2017) evaluated the consolidation parameters of the mixture of Bentonite (90%), and sand (10%) blended with 5%, 10%, and 15% tyre chips of size ranged between 2 to 4.75 mm. With the increase in percentage of tyre chip, reduction in initial void ratio of the mixture was reported which indicated that tyre chips occupied the void spaces of mix. They reported the decline in compression index of the mixture with the addition of tyre chips up to 10%. Further inclusion increased the compression index of the mix, and this was attributed to the compressible of tyre-to-tyre interactions. It was observed that as the content of tyre chips was grown in mixture, the swelling index progressively increased. The elastic nature of tyre chips might have led to increment in swelling index as manifested in Table 2.8. Similarly, improvement in coefficient of consolidation was reported with the addition of tyre chips.

Trouzine et al., (2012) studied the consolidation parameters of low and high plasticity clay soil incorporated with 10%, 20%, 25%, and 50% rubber fibres, by weight. They observed that the compression index values increased gradually with the increase in fibre content in the clay. Likewise, the recompression index of the mixture was reported to be increased with increase in rubber fibre content. It was found 3 to 4 times larger than compression index.

From the review of literature, the effect of rubber tire wastes on consolidation parameters of soil is not clear. Several investigators reported increment while some researchers documented decrement in consolidation parameters of soil incorporated with rubber tire wastes. More investigation is still needed regarding the impact of rubber tire wastes on consolidation parameters of soil. The evaluation of consolidation parameters of cement/lime stabilized clay incorporated with rubber tire wastes is a subject that needs further investigation.

2.2.6 Effect of waste rubber tire inclusion on swelling pressure of fine-grained soils

The swelling pressure of the soil can be used to develop estimates of heave or settlement for given moisture and loading conditions, which plays a major role in design of floor slabs. This section of chapter reviews the effect of inclusion of various forms of rubber tire wastes namely, shreds, granulates (crumbles), fibres (buffings), chips, and ash on swelling percent and swelling pressure of soft/ weak soils.

Al-Tabbaa and Aravinthan, (1998)evaluated the free swelling and swell pressure of clay-tire mixture by using water and paraffin as permeant at three water contents around the optimum moisture content. Two sizes of paraffin treated rubber namely; 1-4 mm and 4-8 mm were added to the clay in varying proportions (6-8%, and 10-15%, by weight). They reported the reduction in free swelling of clay with the incorporation of rubber tires when water was used as permeant. The hairline cracks observed in specimens, which accommodate the water, might have led to decreased free swelling. On contrary, the increase in swelling pressure was observed with the inclusion of rubber tires. It was noted that the use of paraffin as permeant increased the free swelling of clay was negligible. The insignificant increase of free swelling of clay was attributed to the presence of hydrocarbon and diffused double layer. The significant increment in free swelling was observed for clayey soil containing rubber tires when paraffin was used as permeant. A similar trend was seen in swelling pressure test results with paraffin. The swelling pressure of clay was reported to be 5 times smaller when paraffin was used as compared to that of water. Srivastava et al., (2014) studied the swelling pressure of rubberized expansive soil incorporating two different sizes of shredded tires at 10%, 20%, and 30% replacement levels: (i) fine size passing 2.00-0.075 mm retaining and (ii) coarse size passing 4.75-2.00 mm retaining. They mentioned that increasing the shredded tire content leads to a decrease in swelling pressure of the expansive soil. Higher reduction in swelling pressure of expansive soil was reported with the inclusion of coarse size shredded tyres as compared to the corresponding amount of fine size shredded tyres.

Cokca and Yilmaz, (2004) analysed the swelling pressure of fly-rubber-bentonite mixtures (0 to 10% rubber and 10% to 0 bentonite) and reported the decrease in swelling pressure of fly ash bentonite-rubber mixture as the content of rubber increased, and bentonite decreased in the mix.Signes et al., (2016) investigated the effect of rubber crumb (maximum particle size 2 mm) on free swelling of the clayey soil. Clay was partially incorporated with crumb rubber at levels of 0%, 2.5%, 5%, 10%, 15%, 20%, and 25%, by weight. They reported the reduction in free swelling of the clay with the inclusion of crumb rubber as demonstrated in Fig. 2.8. The decreased free swelling was attributed to the partial prevention provided by rubber particles to soil particles against hydration product of smectite.

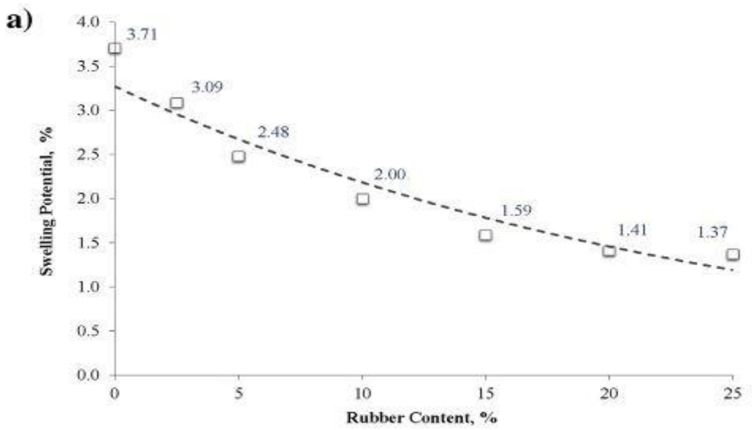


Fig. 2.8 Geotechnical tests swelling potential vs rubber content (Signes et al. 2016)

They restricted the dose of rubber particles up to 3% to meet the requirement of Spanish standards (PG-3, PGP-2008) used for the suitability of material for construction of embankments for both roads and highways.

Patil et al., (2011) investigated the independent effect of silica sand and granulated tire rubber on the behaviour of expansive soil. The expansive soil used in study comprises of 25% of Wyoming sodium bentonite and 75% of clean silica sand of poor gradation. The additives (silica sand and granulated tire rubber) were incorporated in the clayey sand at volume gradation with respect to volume of solids (0, 0.20, and 0.36). The water content of all mixtures was kept constant (12% ± 0.4%). They reported that the swell strain of expansive soil decreased with increase in the percentage of silica fume and granulated tire rubber. The swell strain of specimens incorporated with silica sand was reported to be less than that of specimens incorporated with granulated rubber tire. The study showed that inclusion of silica sand was superior over granular tire rubber in mitigation of swelling of expansive soil. Reduction in swell strain was attributed to the non-expansive characteristics of additives.

Trouzine et al., (2012) evaluated the swell potential and swell pressure of high and low plasticity clay incorporated with rubber fibres of average length of 7 mm in various percentages (10%, 20%, 25%, and 50%, by weight) through swell-consolidation test, reporting a continuous reduction in swelling pressure of both clayey soils with increasing fibre content. The increase in water: clay ratio with the inclusion of rubber fibres due to water absorption capacity of rubber fibres (4%) might be the reason behind reduction in swelling potential. A similar trend was witnessed for the swelling pressure. Kalkan, (2013) evaluated the swelling pressure of clay modified with silica fume and rubber fibres. The experiments were carried out with the rubber fibres (5 to 10 mm length, 0.25 to 0.50 mm thickness, 0.25 to 1.25 mm width) varying from 1% to 4% in a step of 1% and silica fume varying from 10% to 20%. They documented that the inclusion of 10% and 20% of silica fume decreased the swelling of clay from 230 kPa to 33 kPa and 17kPa, respectively. The incorporation of silica fume enhanced the pH value of clay and decreased the relative content of clay minerals. The reduced quantity of relative clay minerals might have led to decrease in swelling pressure of the mix. Likewise, minimum swelling pressure of 17 kPa was reported with tire rubber content of 2% in clay-silica fume mixture having 20% silica fume. The creation of drainage path for the dissipation of pore pressure and resistance provided by the tire fibres against the tensile force was attributed as a reason for decreased swelling pressure. Cabalar et al., (2014) documented the swelling percentages of clay modified the lime and tyre buffing's at the varying proportions of tyre buffing's as 5%, 10%, and 15% and for lime as 2%, 4%, and 6%, by weight. The specimens of clay incorporated with tyre buffing and lime were formulated at (i) optimum water content; (ii) optimum water content-4% (dry side); (iii) optimum water content + 4% (wet side). The inclusion of 5%, 10%, and 15% tyre buffing's reduced the maximum swelling by 14.47%, 33.68%, and 31.31%, respectively. The incorporation of lime reduced the swelling percentage of rubberized clay sharply. This was attributed to the hydration reaction between the lime and clay. They reported that as the water content increased in clay-tyre buffing mixtures, the swelling percentage decreased. The specimens prepared at water content on the wet side of optimum water content were found to be less prone to swelling as compared to specimens prepared at water content on the dry side of optimum water content. The mixtures prepared at lower water content required the higher amount of water for saturation, which led to increase in the volume of the mixtures was credited as the possible reason for such an observation.

From the results reported by various investigators, it can be noted that the inclusion of rubber tire wastes in soil reduced the swelling pressure. On the contrary, a single investigator documented that addition of waste rubber tires to the soil increased the swelling pressure. Further investigation focused on the mechanical/chemical stabilized clayey soil incorporated with rubber tire waste is still needed.

2.2.7 Effect of waste rubber tire inclusion on permeability of fine-grained soils

The property of soils that permits water (fluids) to percolate through its continuously connected voids is called its permeability. The rate of settlement of compressible clay layer under load depends on its permeability. The quantity of stored water escaping through and beneath an earthen dam depends on the permeability of embankment and foundation, respectively. The rate of drainage of water through wells and excavated foundation depends on the coefficient of permeability of soils. Shear strength of soils also depends indirectly on its permeability, because dissipation of pore pressure is controlled by its permeability. This section of the chapter reviews the effect of addition of various forms of waste rubber tires namely, shreds, granulates (crumbles), fibres (buffing's), chips, and ash on permeability of soft/ weak soils.

Al-Tabbaa et al., (1997)studied the effect of particle sizes (1-4 mm, 4-8 mm, and 8-12 mm) and different percentage of the shredded tyre on permeability of kaolin soil. They reported a decrement of 37.93%, 205%, and 205% in permeability of kaolin soil containing 6% shredded tyre of 1-4 mm size, 15% shredded tyre of 4-8 mm size, and 15% shredded tyre of 8-12 mm size, respectively as shown in Table 2.2. The reason cited for permeability reduction were (i) impermeable zones formed by the tire led to reduction of cross section area of flow, (ii) reduction in porosity due to slightly swelling of the tire; (iii) firm bond between soil and tire. The permeability of mixture was reported to be within the range of material to be used as landfill liners. In the similar study, Al-Tabbaa and Aravinthan, (1998) used paraffin treated rubber tire of 1-4 mm (6-8%, by weight) and 4-8 mm (10-15%, by weight) in clayey soil and measured the permeability of clay- tire mixtures using distilled water, acidic water, and paraffin. The increment in permeability of clay-tire mixtures was reported to be insignificant when distilled water was used as permeant because of good bonding which prohibited the formation of pores and cracks. The use of distilled water as permeant for clay-tire mixtures resulted in high permeability due to the flocculation facilitated by acidic environment. A significant reduction in permeability by the use of paraffin as permeant was observed. The permeability of clay incorporated in 15% tires of 4-8 mm size was reported to be reduced by 50 times when paraffin was used as permeant as compared to water. The permeability of clay containing 15% shredded tyre was found in the vicinity with accepted prescribed design values.

Cokca and Yilmaz, (2004)determined the hydraulic conductivity of 7 and 28 days cured specimen of fly ash-bentonite –rubber through the oedometer tests. The content of fly ash was kept fixed (90%) in the mixtures. The content of rubber and bentonite were varied from 0% to 10% and 10% to 0%, respectively. They showed that the hydraulic conductivity of fly ash increased with increasing contents of rubber and decreased with enhancing replacements of bentonite. The hydraulic conductivity of 7 day cured specimen was reported to be twice as that of freshly prepared specimens. 7 and 28 days' hydraulic conductivity of the mixtures was reported to be almost same. The formation of hydration products due to reaction between minerals of clay (aluminous and siliceous) and lime resulted into flocculation and increased the pore size, which ultimately increased the hydraulic conductivity.

Cetin et al., (2006) replaced clay by fine-grained (particle size below 0.425 mm) and coarse-grained (particle size between 2 - 4.75 mm) tire chips at varying proportions of 10%, 20%, 30%, 40%, and 50%, by weight. They experienced that the coefficient of permeability values increased with the increase in tire chip content in the mix and decreased with increase in normal pressure. The permeability of cohesive soil incorporated with tire chips was found to be independent of the size of tire chips.

Table 2.2 Permeability of kaolin and kaolin-tyre mixtures (Al-Tabbaa et al. 1997)

Soil-tyre	**Tyre details**	**Permeability ($x10^{-9}$ ms^{-1})**
Kaolin	0	2.9
Kaolin-tyre	6%, 1-4 mm	1.8
Kaolin-tyre	15%, 4-8 mm	0.85
Kaolin-tyre	15%, 8-12 mm	0.85

Mukherjee and Mishra, (2017)evaluated the hydraulic conductivity of sand-bentonite mixture (90:10) incorporated with 5%, 10%, and 15% tyre chips falling between 4.75-2 mm. As the percentage of tyre chip increased, a consistent increment in hydraulic conductivity of the mixture was observed. The hydraulic conductivity of sand-bentonite mixtures was found to be increased by 3.26, 35 and 466.3 times with the addition of 5%, 10%, and 15%, respectively. This increment in hydraulic conductivity was attributed to the formation of drainage path created by the tyre chips.

Özkul and Baykal, (2007) evaluated the pre-shear and post shear hydraulic conductivity of clay specimens containing 10% tire buffings of 4 to 15 mm length. They observed that the inclusion of rubber fibres did not change the pre-shear hydraulic conductivity of clay significantly. The post shear hydraulic conductivity was observed to be slightly greater than pre-shear values. The small change in hydraulic conductivity was seen in the rubberized clay specimens prepared with standard compaction effort when specimens were sheared up to 20% strain. Kalkan, (2013) examined the hydraulic conductivity of clayey soil incorporated with rubber fibres (1%, 2%, 3%, and 4%, by weight) and silica fume (10% and 20%, by weight). They noticed a decrement in hydraulic conductivity of clay soil with the inclusion of silica fume. The decrement in the hydraulic conductivity of clay from 1.86 x 10^{-7} to 5.53 x 10^{-8} cm/s was observed with the inclusion of silica fume. The very fine particles of silica fume reduced the void ratio might have led to reduced hydraulic conductivity. Contrary to this, the inclusion of rubber fibres increased the hydraulic conductivity of silica fume-clay mixes. The addition of 2% rubber fibres leads to a hydraulic conductivity improvement from 1.86 to 2.86 x10^{-7} cm/s. The ease in movement of water through fibres surface caused an increase in the hydraulic conductivity.

The review of literature establishes that in the majority of cases the addition of rubber tire wastes led to an increase in permeability of the soil. In a few cases, the reduction in permeability of the soil has also been seen. No investigation till yet has been conducted on the impact of rubber tire wastes on the permeability of cement or lime stabilized clayey soil.

2.2.8 Effect of waste rubber tire inclusion on California Bearing Ratio (CBR)of fine-grained soils

The quality and life of the pavement are greatly affected by the type and the quality of subgrade soil. It should have high compressive and shear strength, ease of drainage and low susceptibility to volume changes in all weather conditions. This section of chapter reviews the effect of inclusion of various forms of rubber tire wastes namely, shreds, granulates (crumbles), fibres (buffing's), chips, and ash of rubber tire wastes on California Bearing Ratio (CBR) values of soft/ weak soils.

Priyadarshee et al., (2015) assessed the impact of tire crumbles (4.75-0.150 mm size) on the CBR values of clay and fly ash. Tire crumbles at 1%, 2%, 5%, 10%, and 20% replaced the clayey soil or fly ash, by weight. The load carrying capacity of soil was found to be increased with increasing the rubber content. The marginal improvement in CBR values of clay was reported with the addition of 5% tire crumbles. The increment in frictional component might have led to such observation. The addition of tire crumbles up to 5% in fly ash was reported to be more beneficial as compared to rest of inclusions in improving the load carrying capacity. At the higher content of tire crumbles (i.e. 20%), reduction in load carrying capacity of fly ash was observed. It was documented that the CBR values of clay and fly ash increased with increase in tire crumbles till 5% replacement. Fly ash-tire crumbles mixtures showed higher California Bearing Ratio value than soil-tire crumbles mixtures at up to 5% inclusion due to better gradation. At higher rubber content (beyond 5%), the CBR values for soil-tire crumbles and Fly ash - tire crumbles mixture was found to be equivalent as shown in Fig. 2.9.

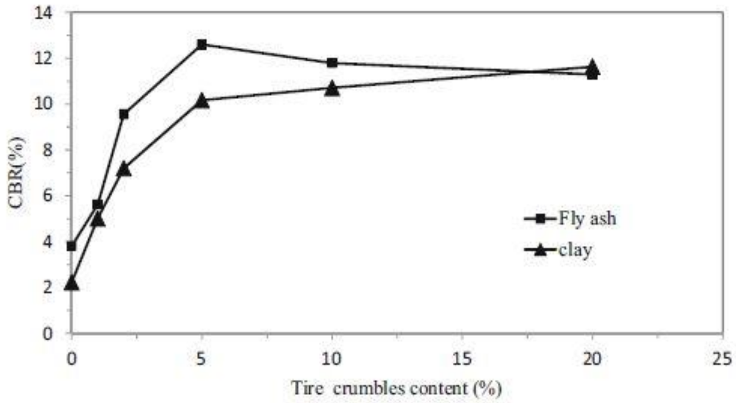


Fig. 2.9 Variation of California bearing ratio with tire crumble content (Priyadarshee et al., 2015)

Tajdini et al., (2016) explored the effect of various proportions (0%, 2.5%, 5%, 7.5%, and 10%) of crumb rubber on CBR value of clayey soil. The inclusion of crumb rubber up to 5% led to an improvement in the CBR value. The improvement in CBR value of clay was approximately 16.4% and 32.8% with the inclusion of 2.5% and 5% crumb rubber, respectively. Further incorporation of crumb rubber (7.5% and 10%) reduced the CBR value of clayey soil. The reduction in CBR value of the clay was approximately 4.1% and 15.6% with the addition of 7.5% and 10% crumb rubber, respectively. The decreased CBR value was accredited to the enhanced interaction between crumb rubber particles either than clay-crumb rubber particles, which led to high deformation of the mix.

Cabalar et al., (2014) evaluated the effect of 5%, 10%, and 15% tyre buffings (ranging between 0.6 and 4.75 mm) and 2%, 4%, and 6% lime content on CBR values of the clayey soil. They stated that the presence of 5%, 10%, and 15% tyre buffing's resulted in a decrease of 26.66%, 62.22%, and 66.66% in CBR values of the clay. The decline in CBR values may be due to (i) reduction in the interaction between the clay particles, (ii) governance of interaction between tyre buffing and (iii) less contribution of tyre buffing in strength development. They reported that loss of CBR values of clayey soil incorporated with tyre buffing could be checked by the inclusion of absolute quantity of lime. The CBR values of clayey soil combined with tyre buffing was found out to be maximum with the addition of

4% lime. The inclusion of lime beyond 4% resulted in a significant loss in the CBR values. Otoko and Pedro, (2014)evaluated the unsoaked and soaked CBR values of two locally available clayey soils of low and high plasticity incorporated with cement (2% and 4%, by weight) and rubber fibres (5%, 10%, and 15%, by weight of 10 to 20 mm length). They found that the maximum CBR value was exhibited by cement stabilized clayey soils at 5% rubber fibres at all ages. With the enhancement in rubber fibres beyond 5%, the CBR values decreased. The soaked CBR values of all mixture were reported to be less than unsoaked CBR values.

In the light of above literature review, it can be concluded that addition of rubber tire wastes up to optimum dose increased the CBR values of the soil. Few studies show that the incorporation of rubber tire wastes decreases the CBR values of clay. Studies about the effect of cement/lime on the California Bearing Ratio of rubberized soil are scarce.

2.2.9 Effect of waste rubber tire inclusion on leachability of fine-grained soils

Incorporation of rubber tire waste in soil may lead to contamination of the water bodies. The consumption of chromium and Iron contaminated water results into several diseases like anemia, stomach cancer, heamochromatosis, etc. This section of the chapter reviews the effect of inclusion of various forms of rubber tire wastes namely, shreds, granulates (crumbles), fibres (buffing's), chips, and ash of rubber tire wastes on leachability of soft/ weak soils.

Al-Tabbaa et al., (1997)conducted the TCLP (Toxicity Characteristic Leaching Procedure) leaching test for evaluating the effect of shredded tire incorporation on concentration of iron and zinc minerals of kaolin, kaolin-lime, and bentonite soils. Three sizes of shredded tyre ranged between 1-4 mm, 4-8mm, and 8-12 mm were used. The inclusion level for 1-4 mm size shredded tyre was 6% and 4-8 mm and 8-12 mm was 15%, respectively. They observed that the concentration of leached iron in soil-tyre mixtures was more than maximum allowable level. Only the specimens of kaolin-lime mixture containing 15% tire of 8-12mm size fulfil the requirement of maximum allowable concentration specification for drinking water. The size of tire produced higher leachate concentration of heavy material because of the large surface area was attributed as primary reason behind the increased concentration. The concentration of zinc was reported to be within the maximum allowable limit for all the mixtures as shown in Table 2.3. They suggested that the soil-shredded tyre combinations are needed to be supplemented with some stabilizers before application to prevent the adverse effect of leaching. In an identical study, the leachability of clay- shredded tire mixtures was investigated by Al-Tabbaa and Aravinthan, (1998) through NRA (National River Authority) recommendation test and TCLP (Toxicity characteristic leaching procedure) leaching tests. Rubber tires of 1-4 mm and 4-8 mm sizes were treated with paraffin and were incorporated in percentage of 6-8% and 10-15%, respectively. The concentration of copper and nickel were measured for mixtures. A comparison between the obtained concentration and standards of drinking water suggested by Severn Trent Laboratories was made. Clay mixtures formulated with 1-4 mm sized rubber tires showed a higher concentration of copper and nickel as compared to 4-8 mm size rubber particles. The concentration of products by TCLP test was reported to be more than NRA recommended test. The concentration of copper by NRA test at 100% tire of size 4-8mm and clay-tire mixtures with 15% tire of size 4-8mm was reported to be same.

Table 2.3 Concentration of iron and zinc in the leachate samples (Al-Tabbaa et al. 1997)

Soil-tyre mix	Tyre size mm	Tyre %	pH	Iron (mgL^{-1})	Zinc (mgL^{-1})
tyre	1-4	100	4.8	10.29	10.37
tyre	4-8	100	4.7	7.52	8.57
tyre	8-12	100	4.8	5.91	5.32
kaolin		0	4.7	0.36	0.51
Kaolin-tyre	1-4	6	4.7	0.72	1.91
Kaolin-tyre	4-8	15	4.6	0.88	1.79
Kaolin-tyre	8-12	15	4.7	1.00	1.29
Kaolin-lime		0	11.1	0.24	0.07
Kaolin-lime-tyre	1-4	6	10.8	0.28	0.066
Kaolin-lime-tyre	4-8	15	10.4	0.24	0.049
Kaolin-lime-tyre	8-12	15	10.6	0.20	0.045
bentonite		0	4.8	0.80	0.24
Bentonite-tyre	1-4	6	4.8	1.05	0.55
Bentonite-tyre	4-8	15	4.7	1.24	0.617
Bentonite-tyre	8-12	15	4.7	3.24	0.676
drinking water standards*				0.20	5.00

Cokca and Yilmaz, (2004) performed the leachate analysis on fly ash-bentonite-rubber mixtures. Seven mixtures containing 90% fly ash were prepared by inclusion of 0%, 1%, 3%, 5%, 7%, 9%, and 10% rubber and 10%, 9%, 7%, 5%, 3%, 1%, and 0% bentonite. The atomic absorption tests were used for chemical analysis of mixtures obtained from extraction process and compared the results with Environmental Protect Agency (EPA) standards. The concentration of hazardous elements such as cadmium, lead, selenium, barium, mercury, arsenic, chromium, and silver was found to be lower than the limit specified by EPA standards.

Very less investigation have been conducted on the leachability of soil containing rubber tire wastes. Few studies show that the contamination of water due to the inclusion of rubber tire wastes in the soil is within the limits of the drinking water standards provided by various agencies. While some researchers documented that the soil-rubber tire wastes mixtures require chemical stabilization to meet the standards. The leachability of soil incorporated with rubber tire wastes and chemical stabilizers is a subject that needs further investigation.

2.2.10 Effect of waste rubber tire inclusion on durability of fine-grained soils

The most crucial parameter to assess the suitability of any construction material is its durability. The durability of cement –stabilized soils can be predicted by tube suction, 7-day unconfined compression strength, wetting–drying cycles and freezing–thawing cycle’s tests. The durability of the composite depends upon the pore structure, tensile strength, inter-particle friction and cohesion of the materials. This section of the chapter summaries the research work carried out by various investigators on durability aspect of clayey soil incorporated with different forms of rubber tire wastes namely, shreds, granulates (crumbles), fibres (buffing’s), chips, and ash.

The effect of freeze/thaws cycles on hydraulic conductivity, unconfined compressive strength, split tensile strength, and coefficient of volume change of fly ash- bentonite-rubber mixture incorporated with (0%, 5%, and 10%) rubber and (10%, 5%, and 0%) bentonite was studied by Cokca and Yilmaz, (2004). They reported an improvement in hydraulic conductivity of mixtures after freeze/thaw cycles. After freeze/thaw cycles, a reduction of about 50% reduction in unconfined compressive strength of mixtures was reported when compared to the strength before freeze/thaw cycles. The decrement in split tensile strength was also reported after the freeze/thaw cycle. A very little change in coefficient of volume change of mixtures was seen after the freeze-thaw cycles and it was considered insignificant by the authors.

Jafari and Esna-ashari, (2012) assessed the impact of three freeze-thaw cycles on unconfined compressive strength of clayey soils stabilized with 0%, 4%, and 8% lime and reinforced with 0%, 0.5%, 1%, and 1.5% waste tire cord of 20 mm length. They reported that addition of fibres up to 1.5% enhanced the strength of unstabilized and stabilized clay. It was found that the unstabilized specimens disintegrated completely after two cycles. The strength of reinforced specimens stabilized with 4% lime after each cycle was found more than the samples stabilized with 8% lime. The difference in strength was attributed to the presence of free lime in specimens, which led to the lack of cohesion and increased the sensitive of the specimens against freeze-thaw cycles. With increasing the number of cycles, the reduction in strength of samples was observed. A significant difference between the strength of lime stabilized unreinforced and lime stabilized reinforced specimens was found. This was accredited to generation of internal pressure in the matrix due freezing of pore water in case of unreinforced lime stabilized samples. Whereas, in the case of reinforced lime stabilized specimens, the interlocking of fibres with rest of composite restricted the movement of particles due to the development of friction at interfacial contact area might have led to such results. The stress-strain response of reinforced soil after one cycle showed a loss in strength and stiffness. It was observed that introduction of fibres in the lime stabilized specimens reduced the rate of reduction of strength and stiffness.

In past, the insufficient amount of investigations has been carried out on durability of unstabilized and stabilized fine-grained soil. From the literature mentioned above, it can be noted that rubber tire waste in the soft/ weak soil decreased the durability. Indeed, the durability studies on fine-grained soil containing rubber tire wastes and cement/lime still need more experimental investigation to confirm the results.

2.2.11 Effect of waste rubber tire inclusion on dynamic properties of fine-grained soils

This section of the chapter focuses on work carried out by various investigators on the dynamic behaviour of clay-rubber tire waste mixtures.

Kim and Kang, (2013) conducted elastic wave test on CGM formed by blending clay-crumb rubber- cement- bottom ash. The inclusion of crumb rubber reduced the elastic wave velocities of CGM and resulted in reduced shear modulus values. However, contrary propensity was witnessed when 0 % to 100% bottom ash was incorporated. At 0-25% incorporation of rubber, the lower shear modulus was achieved that might be due to sand like behaviour of rubber. Whereas, the inclusion of 50-100 % rubber content exhibited, rubber-like behaviour led to the further reduction of shear modulus.

Chan, (2012) conducted blender element test on cement stabilized clayey sand incorporated with rubber chip or shreds. The magnitude of S and P wave velocity increases as the content of cement increases in mix whereas it decreases as the quantum of rubber increases. She reported that the velocities of S wave of mixture containing rubber shreds and rubber chips are similar and velocity of P wave stayed close as demonstrated in Fig. 2.10(a). She reported that cement was the dominant factor for enhancing the stiffness of mix. The shear modulus of rubberized clay containing 4% cement was found more as shown in Fig. 2.10(b). The inclusion of rubber beyond 2% in cement clayey sand obliterates the effect of cement.

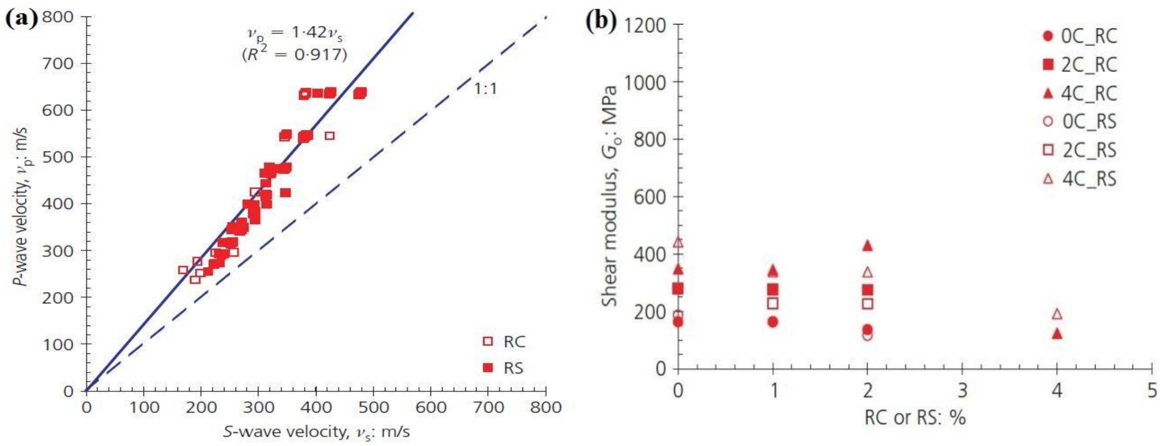


Fig. 2.10 (a) v_p plotted against v_s , (b) Shear modulus (G_o) plotted against rubber content (Chan, 2012)

Akbulut et al., (2007) examined the dynamic properties such as damping ratio and shear modulus of soil-rubber fibres mixtures through resonant frequency tests. Three types of highly plastic clayey were amended with rubber fibres of 5 mm, 10 mm, and 15 mm length varying from 1% to 5% in step of 1%. It was found that the damping ratio and shear modulus exhibited maximum enhancement with increasing the percentage of rubber fibres of 10 mm up to 2%. After that, a slight reduction was noticed.

The researchers have carried out limited studies in the past on dynamic properties of rubberized clay. The majority of the published research articles show that rubberization of soil lead to an increase in shear modulus and damping ratio. Few authors documented the opposite trend. Still, more research is needed to confirm the results of other investigators. Besides, an investigation focused on the effect of inclusion of cement/lime and rubber tire wastes on dynamic properties of clay is needed.

2.3 USABILITY OF FINE GRAINED SOIL-WASTE RUBBER TIRE MIXTURES

The possible applications of fine-grained soil-waste rubber tire mixtures suggested by the researchers are:

- As a filler material in road and railway embankments (Xin et al., 2015; Srivastava et al., 2014)
- As land cover and landfill liners (Cokca and Yilmaz, 2004; Mukherjee and Mishra, 2017; Al-Tabbaa & Aravinthan, 1998)
- For base and sub-base of low traffic volume roads (Guleria and Dutta, 2013; Cabalar et al., 2014; Kalkan, 2013)
- Backfill materials for residential foundations, retaining walls, and land reclamation (Kim and Kang, 2013; Srivastava et al., 2014)
- For manufacturing of roofing tiles (Sarvade & Shet, 2012).
- Construction of pedestrian, car parks and foundation pad for small machinery. (Parasivamurthy et al., 2006; Akbulut et al., 2007; Wang and Mei, 2012)
- For trench filling and pipe bedding and paving slabs (Parasivamurthy et al., 2006)
- Cold resistance layer in seasonal frost zone (Jafari & Esna-ashari, 2012).

2.4 CONCLUDING REMARKS

Consideration of detrimental impression induced by improper disposal of waste rubber tire on health, environment, and ecological system, urgently generates concern among the scientific community. The number of investigators has made some serious efforts worldwide on the utilization of waste rubber tire in concrete, asphalt pavement, waterproofing system and membrane liner, etc. The voluminous consumption of this hazardous waste is possible either in concrete industries or for soil stabilization. Especially, soils have a tremendous potential to imbibe this non-biodegradable and dangerous waste because of its wider applications. The incorporation of waste rubber tire in soils may lead to complete utilization this waste because of its enormous consumption, which ultimately results in sustainable development and cleaner production for rubber industries.

An extensive research work carried out by other investigators on the effect of waste rubber tire incorporation on geotechnical properties namely, Atterberg's limits, compaction parameters, strength, swelling, consolidation, permeability, California bearing ratio, leachability, durability and dynamic properties of fine-grained soils have been reviewed in this chapter. Investigations carried out till today on the geotechnical properties of fine-grained soil-waste rubber tire mixtures can be remarked as follows:

- The most studies reported on Atterberg's limits of fine-grained soil-ELT mixtures believed that the inclusion of waste rubber tire reduced the liquid limit, plastic limit, and shrinkage limit. On the other hand, few investigators concluded that addition of waste rubber tire increased the Atterberg's limits.
- The majority of studies believed that the inclusion waste rubber tire in fine-grained soil reduced the maximum dry unit weight and optimum moisture content. On the other hand, few investigators concluded that addition of waste rubber tire increased the optimum moisture content.
- The incorporation of waste rubber tires up to optimum value in the mixture improved the shear strength parameters (angle of internal friction and cohesion) as believed by many researchers. Beyond optimum dose, the shear parameters decreased.
- Waste rubber tire addition reduced the tensile strength of fine-grained soil.
- Many investigators mentioned that the consolidation characteristics such as compression index, swelling index, recompression index and coefficient of volume change of fine-grained soil were improved by adding waste rubber tire. While few, researchers have pointed out that, the incorporation of waste rubber tire reduces these consolidation characteristics.
- The inclusion of waste rubber tire in fine-grained soil reduced its swelling percent and swelling pressure.
- Increment in permeability of fine-grained soil was observed with the addition of waste rubber tire.
- The majority of investigators believed that inclusion of waste rubber tire up to a certain limit in the fine-grained soil improved its California bearing ratio.
- Although little work has been carried out on the leachability of fine-grained soil-waste rubber tire mixtures in the past, the available literature showed that the contamination of water bodies due to waste rubber tire inclusion is within the permissible limits.

It can be concluded that fine-grained soils have an enormous feasibility to utilize rubber tire wastes. The incorporation of various form of waste rubber tire namely, shreds, granulate (crumb), fibres (buffing's), chips, and ash in soil would not only solve the issues of landfilling, stockpiling and burning of waste rubber tires, but also open a new perspective for improvement in the geotechnical properties of fine-grained soil.

2.5 Knowledge Gaps

The majority of past studies are confined to compaction and shear strength of the fine-grained soil-waste rubber tire mixtures. Insufficient amount of research work has been carried out in the past on tensile strength, consolidation characteristics, swelling pressure, and durability of soil-waste rubber tire mixtures. A comprehensive study focusing on all properties of mixture is needed urgently for field applications. Little work has been carried out on fine-grained soil-waste rubber mixtures containing lime or cement. Research works addressing the impact of cement or lime stabilization on geotechnical properties of fine-grained soil-waste rubber tire mixtures is still required to solidify the results reported by other investigators. The utilization of waste rubber tires in uncemented and cemented clayey soil would not only solve the problem associated with fine-grained soil such as low strength, high compressibility, and low permeability, but also open a new avenue for disposal of this hazardous waste.

A detailed plan of investigation is presented in Chapter 3.

CHAPTER 3

CHARACTERIZATION OF MATERIAL AND METHODOLOGY

3.1 GENERAL

As outlined in the previous Chapter, it is proposed to study the behaviour of clayey soil-cement-rubber crumbles/fibres mixtures. This chapter presents the details about materials and experimental procedures adopted along with the apparatus used and a summary of test programme.

3.2 MATERIAL

3.2.1 Soil

The soil sample used in the investigation was taken area nearby Jaipur. The particle size distribution curve of soil sample is shown in Fig. 3.1. The geotechnical properties of soil sample obtained by using relevant Indian standards are listed in Table 3.1. The mineralogical phases present in soil was studied by X-ray diffraction pattern. For this purpose, PANalytical X'pert PRO Powder diffractometer was used. The soil sample used in this investigation consists of high Illite content with quartz and some kaolinite as shown in Fig. 3.2(a). The other minerals such as Calcite ($CaCCO_3$), Hercynite (Al_2FeO_4), Kaolinite and iron oxides such as Magnetite (Fe_3O_4) and Hematite (Fe_2O_3), which occur in the crystalline form, are interpreted by the peak characteristic. The scanning electron micrograph of clay shows the agglomeration of fine clay particles (as shown in Fig. 3.2(b))

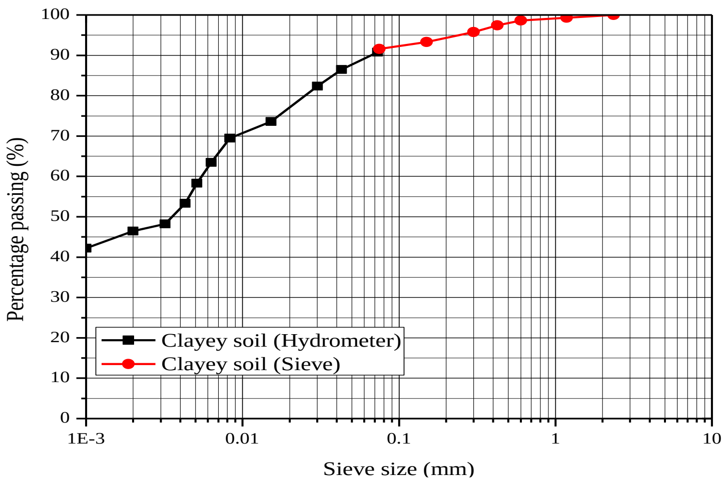


Fig. 3.1 Grain size distribution curve of soil

Table 3.1 Geotechnical properties of soil

Soil properties	Indian Standard used	Values
Specific gravity	IS:2720 (Part 3)-1980	2.69
Grain Sizes (%)		
Gravel	IS:2720 (Part 4)-1985	0.0
Sand	IS:2720 (Part 4)-1985	7.8
Silt	IS:2720 (Part 4)-1985	31.5
Clay	IS:2720 (Part 4)-1985	60.7
Liquid Limit (%)	IS:2720 (Part 5)-1985	34.2
Plastic Limit (%)	IS:2720 (Part 5)-1985	24.8
Plasticity Index (%)	IS:2720 (Part 5)-1985	9.4
Soil Type	IS : 1498-1970	CI
Maximum Dry Unit Weight (kN/m^3)	IS:2720 (Part 8)-1983	16.35
Optimum Moisture Content (%)	IS:2720 (Part 8)-1983	20.89

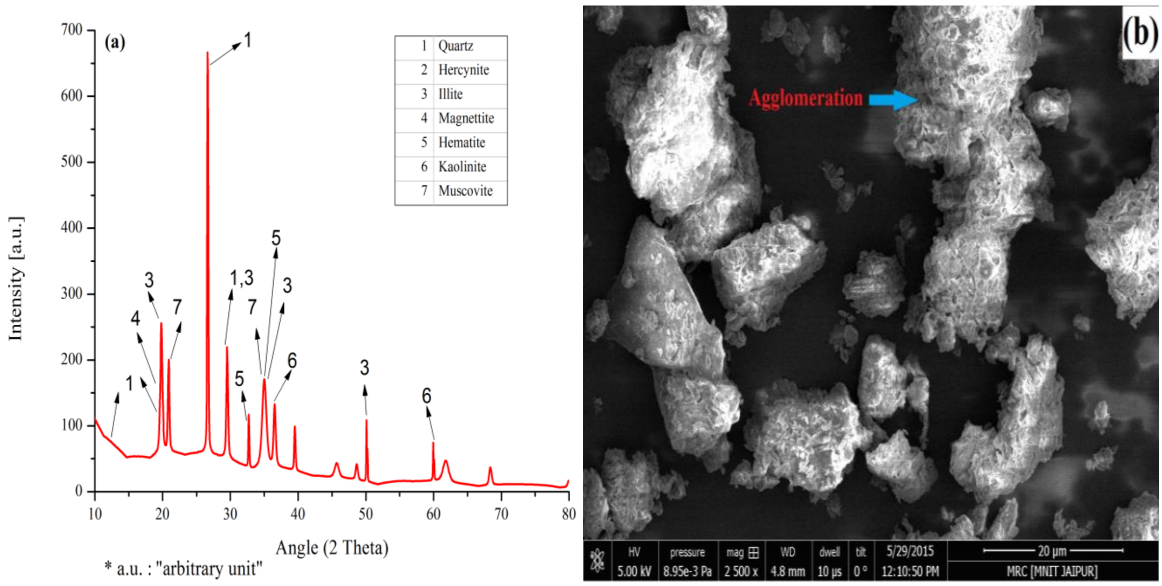


Fig. 3.2 (a) X-ray diffraction pattern of soil sample, **(b)** SEM image of soil sample at 2500-x magnification

3.2.2 Cement

The locally available Ordinary Portland Cement (OPC-43 grade) of Binani Cement Company was used in this study. Table 3.2 illustrates the physical characteristics of cement evaluated by using relevant Indian standard codes of practice. Furthermore, the chemical composition of cement as provided by the manufacturer is also tabulated in Table 3.3.

Table 3.2 Physical properties of cement

Properties	**Indian Standard used**	**Values**
Fineness	IS: 4301-1 (1996)	3.5
Specific gravity, G	IS: 4301-11 (1988)	3.12
Standard consistency, %	IS: 4301-4 (1988)	39
Initial setting time, minutes	IS: 4301-5 (1988)	35
Final setting time, minutes	IS: 4301-5 (1988)	600
Soundness (Expansion, mm)	IS: 4301-3 (1988)	4

Table 3.3 Chemical composition of cement

Characteristic	**Content***
Lime Saturation Factor (%)	0.78
Alumina Iron Ratio (%) Min.	0.69
Insoluble Residue (%) Max	3.60
Magnesia (%) Max.	5.75
Sulphuric Anhydride (%) Max.	3.20
Loss on Ignition (%) Max.	4.88

*As provided by the manufacturer

3.2.3 Rubber Crumbles

The rubber crumbles procured from S&J Granulate solution, Mumbai, India was used in this investigation. Most of the particles ranged from 0.8–2 mm with a specific gravity of 1.13 as shown in Fig. 3.3. Fig. 3.4 illustrates the particle size analysis of rubber crumbles. It had an effective size (D_{10}), uniformity and curvature coefficient of 0.80, 1.48, and 1.40, respectively. Its chemical properties are tabulated in Table 3.4 as provided by the supplier. The photography and scanning electron microscopy image of rubber crumbles are shown in Fig. 3.5(a) and 3.5(b). Fig. 3.5(b) indicates that the rubber crumbles particle used in this investigation are almost irregular in shape.

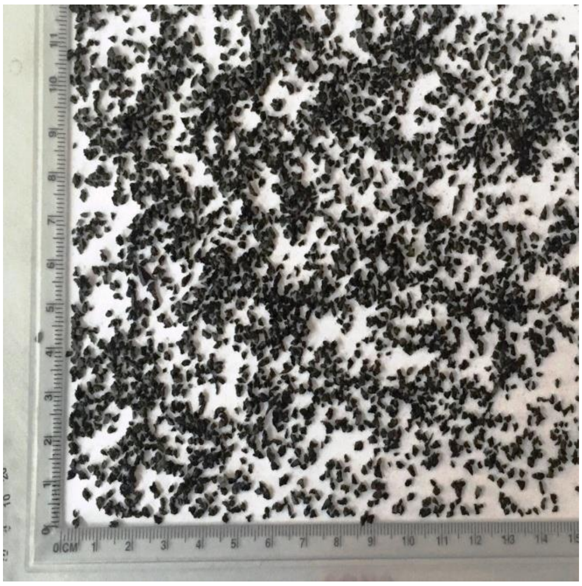


Fig. 3.3 Rubber crumbles

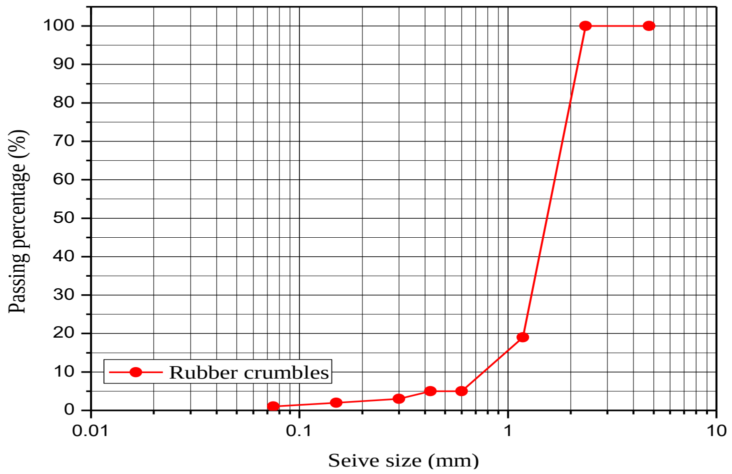


Fig. 3.4 Particle size distribution curve of rubber crumbles

Table 3.4 Chemical composition of rubber crumbles

Test	Results*
Ash content, %	5.11
Carbon black content, %	28.43
Acetone extract, %	9.85
Volatile matter, %	0.56
Hydrocarbon content, %	56.05
Polymer analysis	SBR

*As provided by the manufacturer

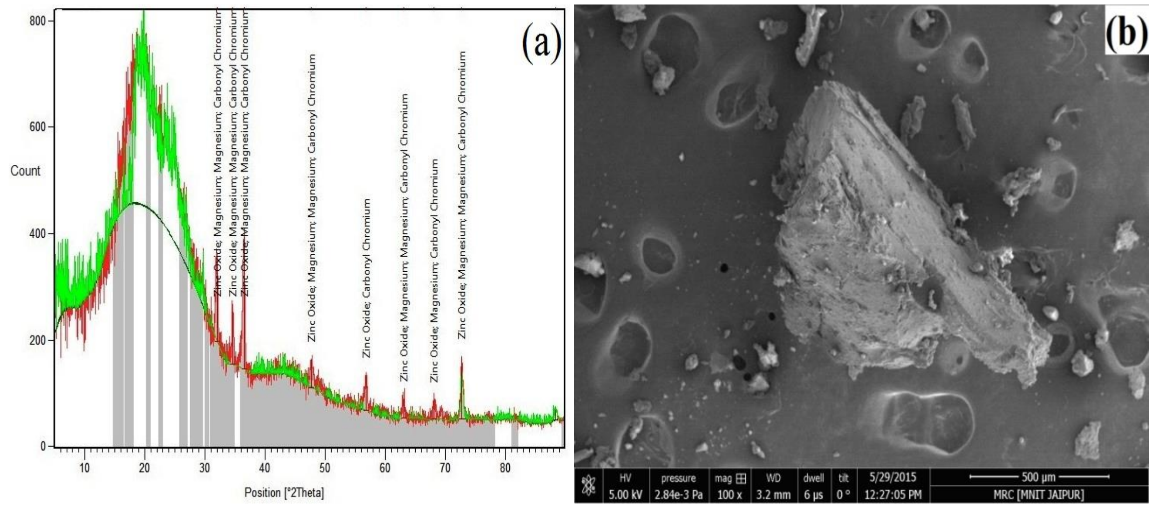


Fig. 3.5 (a) X-ray diffraction of rubber crumbles, **(b)** SEM image of rubber crumble at 100 x magnification

3.2.4 Rubber Fibres

Rubber fibres of specific gravity 1.07, obtained from the mechanical grinding of waste rubber tires were used in this investigation. The gradation curve of rubber fibres has been shown in Fig. 3.6. The rubber fibres of 2-3 mm width (approx.) and 15 mm length (max.) as shown in Fig. 3.7(a) were used. The modulus of elasticity and tensile strength of the rubber fibres were 1.72 MPa and 22.8 MPa, respectively. To ascertain the compatibility of waste rubber fibres with the clayey soil, the chemical composition and microstructural studies were needed. The energy dispersive X-ray analyzer (EDAX) and scanning electron microscopy (SEM) of rubber fibres were carried out. The result of EDAX analysis as tabulated in Table 3.5 shows the high percentage of carbon in sample of rubber fibre. The presence of carbon and shape of the rubber fiber particles could strongly influence the properties of proposed composite. The cavity and micro-cracks were observed from SEM image of rubber fibre as shown in Fig. 3.7(b). These flaws affect the interfacial bonding of rubber fibres with composite (Segre and Joekes, 2000; El-Tayeb and Nasir, 2007; Reha Taha et al., 2008; Gupta et al., 2014, 2016, 2017).

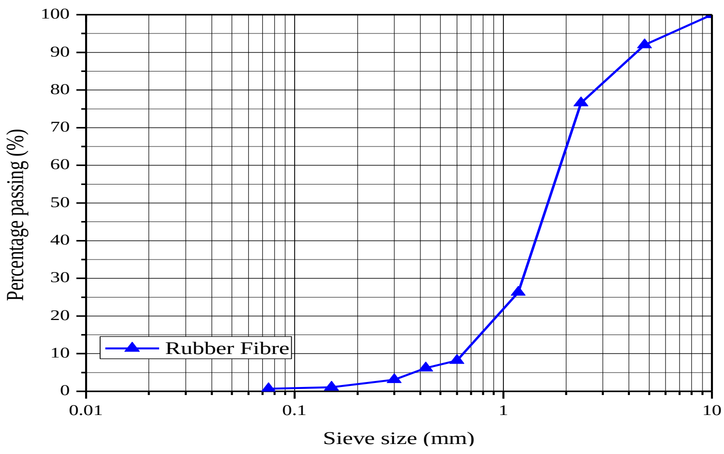


Fig. 3.6 Grain size distribution curve of rubber fibres

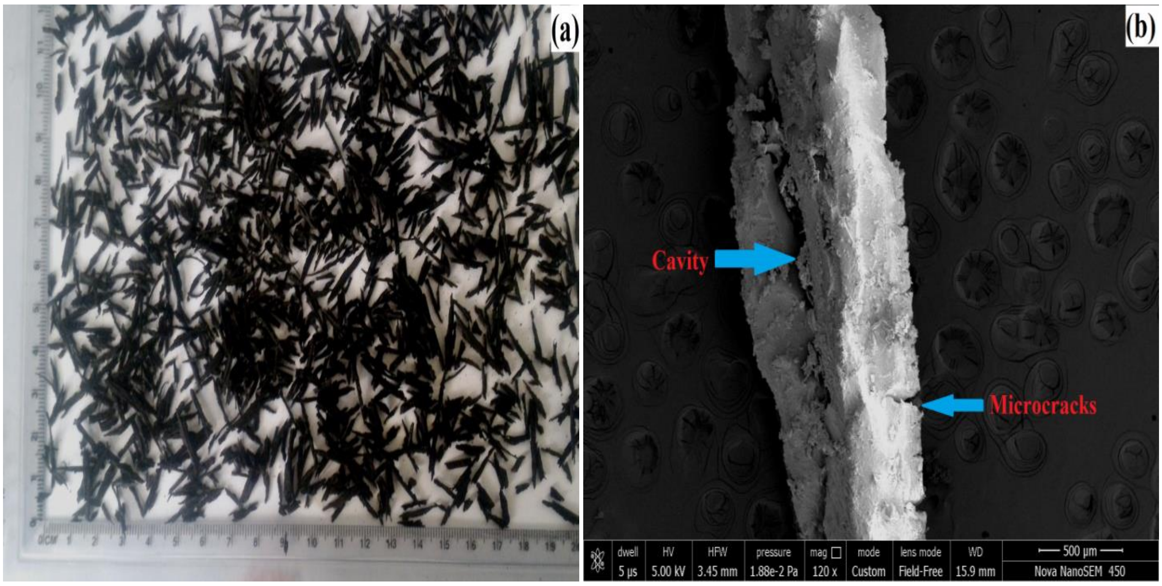


Fig. 3.7(a) Rubber fibres, **(b)** SEM image of rubber fibre at 120-x magnification

Table 3.5 Chemical composition of rubber fibres (%)

Composition of element	Symbols	Percentage (%)
Carbon	C	87.51
Oxygen	O	9.23
Zinc	Zn	1.76
Sulfur	S	1.08
Silicon	Si	0.20
Magnesium	Mg	0.14
Aluminum	Al	0.08

3.3 PROPORTION OF MIXTURES

The clay was mixed with different proportions of rubber crumbles/fibres and cement in this investigation. The quantity of cement used for the stabilization was selected on the basis of past research work carried out by other investigators on the stabilization of clayey soils using cement (Tang et al., 2007; Kaniraj and Havanagi et al., 2001; Cabalar and Karabash, 2015). In a study carried out by Kaniraj and Havanagi, (2001) on cement-stabilized fiber-reinforced fly ash-soil mixtures, 3% and 6% cement content were used for the stabilization. Tang et al., (2007) had used 3% and 8% cement content for the stabilization of clayey soil in his investigation on clayey soil stabilized with cement and reinforced with short polypropylene fibers. Kumar and Gupta, (2016) had used 2% and 4% cement content for stabilization of fiber-reinforced pond ash, rice husk ash–soil mixtures. Cabalar and Karabash, (2015) incorporated 3% and 5% cement content in his investigation on the utilization of tire buffing and cement as a sub-base material modifier. According to MORD specifications (2014) (Ministry of Rural Development: Specification of Rural Roads Published by Indian Road Congress, 2014), clause 404 the clayey soil having PI less than 15%, 3-8% cement content can be used for stabilization. The content of rubber crumbles/fibres to be incorporated in cement stabilized clayey soil was decided on the basis of investigation carried out by other researchers, which have already been discussed in the previous chapter.

The percentages of rubber crumble/fibre used in this investigation were 0%, 2.5%, 5%, 7.5%, and 10% and cement were 3% and 6% of the total mass of clay. Initially, it was decided to incorporate rubber crumbles/fibres varying from 2.5% to 15% at an increment of 2.5% (by the weight of dry soil). The results of the trials showed that inclusion of rubber crumbles/fibres beyond 10% is not practically possible because the specimens of rubberized clayey soil disintegrate while removing from the mould. The disintegration of specimens at higher rubber content may be accredited to high elasticity of rubber particles with leads to returning of rubber particles to its initial state after removal of compactive effort. Gupta et al. (2016)also reported difficulty in the packing of concrete at higher replacement level of natural fine aggregates with rubber particles. Based on trial results the rubber crumbles/fibres content in mixtures were restricted up to 10%.

Five combinations of clay, cement and rubber crumbles/fibres were prepared. The cement content of 0%, 3%, and 6% and rubber crumbles/fibres content of 0%, 2.5%, 5%, 7.5%, and 10% by the weight of soil were chosen. The descriptions of various combinations are presented in Table 3.6. The weight of mixture contains clayey soil-rubber crumbles/fibres, clayey soil-cement, and clayey soil-cement-rubber crumbles/fibres were quantified according to the formulas given below:

$$W_{SRc} = W_S + W_{Rc} \quad (3.1)$$

$$W_{SRf} = W_S + W_{Rf} \quad (3.2)$$

$$W_{SC} = W_S + W_C \quad (3.3)$$

$$W_{SCRc} = W_S + W_C + W_{Rc} \quad (3.4)$$

$$W_{SCRf} = W_S + W_C + W_{Rf} \quad (3.5)$$

where W_{SRc}, W_{SRf}, W_{SC}, W_{SCRc}, and W_{SCRf} are the weight of five combinations of clayey soil-rubber crumbles, clayey soil-rubber fibres, clayey soil-cement, clayey soil-cement-rubber crumbles, and clayey soil-cement-rubber fibres, respectively and W_S, W_C, W_{Rc}, and W_{Rf} are the weight of clayey soil, cement, rubber crumbles and rubber fibres, respectively.

Table 3.6 Details of Clay-Cement- Rubber crumbles/fibres mixtures

$W = W_S + W_C + W_{Rc}$ or W_{Rf}	**Variation of W_S**	**Variation of W_C**	**Variation of W_{Rc}**	**Variation of W_{Rf}**
	(% by total dry weight)			
Combination 1	100, 97.5, 95, 92.5, 90	0	0, 2.5, 5, 7.5, 10	0
Combination 2	97.5, 95, 92.5, 90	0	0	2.5, 5, 7.5, 10
Combination 3	97, 94	3, 6	0	0
Combination 4	94.5, 92, 89.5, 87, 91.5, 89, 86.5, 84	3, 6	2.5, 5, 7.5, 10	0
Combination 5	94.5, 92, 89.5, 87, 91.5, 89, 86.5, 84	3, 6	0	2.5, 5, 7.5, 10

3.4 CODIFICATION

For the better understanding of results, the codification of mixtures was used. The mix designations along with their proportions are shown in Table 3.7 and 3.8. The specimen of untreated clay (without cement and rubber crumbles/fibres) was coded as S_{ref} and was taken as reference mix. Other mixes were represented by three capital alphabets, and each alphabet was followed by a numeric value in subscript. The numeric value in subscript indicates the percentage of clay, cement and rubber crumbles or fibres in the mix. For example, '$S_{94.5}C_3Rc_{2.5}$' represents a mix containing 94.5% of clayey soil, 3% of cement, and 2.5% of rubber crumbles. The alphabets 'S', 'C', and 'Rc' represented the clayey soil, cement, and rubber crumbles, respectively. Similarly, '$S_{94.5}C_3Rf_{2.5}$' represents a mix containing 94.5% of clayey soil, 3% of cement, and 2.5% of rubber fibres. The alphabets 'S', 'C', and 'Rf' represented the clayey soil, cement, and rubber fibres, respectively.

Table 3.7 Mix designations and their proportions for Clay-Cement- Rubber crumble mixtures

Mix Designation	**Clayey soil**	**Materials (%)**		
		Cement	**Rubber crumble**	**Total**
S_{ref}	100	0	0	100
$S_{97.5}C_0Rc_{2.5}$	97.5	0	2.5	100
$S_{95}C_0Rc_5$	95	0	5	100
$S_{92.5}C_0Rc_{7.5}$	92.5	0	7.5	100
$S_{90}C_0Rc_{10}$	90	0	10	100
$S_{97}C_3Rc_0$	97	3	0	100
$S_{94}C_6Rc_0$	94	6	0	100
$S_{94.5}C_3Rc_{2.5}$	94.5	3	2.5	100
$S_{92}C_3Rc_5$	92	3	5	100
$S_{89.5}C_3Rc_{7.5}$	89.5	3	7.5	100
$S_{87}C_3Rc_{10}$	87	3	10	100
$S_{91.5}C_6Rc_{2.5}$	91.5	6	2.5	100
$S_{89}C_6Rc_5$	89	6	5	100
$S_{86.5}C_6Rc_{7.5}$	86.5	6	7.5	100
$S_{84}C_6Rc_{10}$	84	6	10	100

Table 3.8 Mix designations and their proportions for Clay-Cement- Rubber fibres mixtures

Mix Designation	Clayey soil	Materials (%)		
		Cement	Rubber fibre	Total
$S_{97.5}C_0Rf_{2.5}$	97.5	0	2.5	100
$S_{95}C_0Rf_5$	95	0	5	100
$S_{92.5}C_0Rf_{7.5}$	92.5	0	7.5	100
$S_{90}C_0Rf_{10}$	90	0	10	100
$S_{94.5}C_3Rf_{2.5}$	94.5	3	2.5	100
$S_{92}C_3Rf_5$	92	3	5	100
$S_{89.5}C_3Rf_{7.5}$	89.5	3	7.5	100
$S_{87}C_3Rf_{10}$	87	3	10	100
$S_{91.5}C_6Rf_{2.5}$	91.5	6	2.5	100
$S_{89}C_6Rf_5$	89	6	5	100
$S_{86.5}C_6Rf_{7.5}$	86.5	6	7.5	100
$S_{84}C_6Rf_{10}$	84	6	10	100

3.5 SAMPLE PREPARATION

Table 3.9 shows the specimen size varied for conducting various tests.

Table 3.9 Specimen size for various tests

Tests	Specimen Size
Unconfined compressive strength	38.1 mm diameter and 76.2 mm height
Split tensile strength	38.1 mm diameter and 76.2 mm height
California bearing ratio	150 mm diameter and 175 mm height
One-dimensional consolidation	60 mm diameter and 20 mm height
Swelling pressure	60 mm diameter and 20 mm height
Durability	100 mm diameter and 127.3 mm height

First, the dry mixtures of clayey soil and rubber crumbles/fibres were prepared in a laboratory mixer as per requirement. The prepared mixtures were then stored in plastic bags for future use. Cement was incorporated in the prepared mixture at the time of formation specimens. The desired quantity of water (optimum moisture content) which was added to the particular mix was obtained by Modified Proctor test performed as per IS: 2720 (Part 8)-

1983. The moisture content was measured by drying the sample of the mix in the oven. Special care was taken for homogeneity and uniformity of the mixes at each stage of mixing.

3.5.1 Sample preparation for Unconfined Compression Strength and Split Tensile Strength Tests

For determination of unconfined compression strength and split tensile strength of the various mixtures of clayey soil-cement-rubber crumbles/fibres, the specimens of 38.1 mm dia. and 76.2 mm length were prepared at their respective maximum dry unit weight and optimum moisture content (as mentioned in chapter 4, 5, and 6). A metallic mould having size 38.1 mm inner diameter and 76.2 mm long was used. The samples were compacted to a known volume by tamping until the desired unit weights were reached. The specimens so obtained were extracted from the mould by using sample extractor (Fig. 3.8(b)). Three identical specimens of each combination were prepared to minimize the error due to materials, test conditions and for making test results more reliable. For the cemented mixtures, two sets of samples were prepared for unsoaked and soaked conditions. All the specimens were kept in air tight polythene bags (Fig. 3.8(c)) and stored in a humidity controlled room at 25^0C temperature and 96% humidity, respectively for a curing period of 7, 14 and 28 days. For soaked condition, the specimens were immersed in water for 24 hrs prior of testing (Fig. 3.8(d)).

Fig.3.8 Sequential steps for sample preparation for unconfined compressive strength and split tensile strength testing from: (a) to (d)

3.5.2 Sample preparation for California Bearing Ratio Tests

The specimens of California Bearing Ratio tests were prepared at maximum dry unit weight and optimum moisture content of the mixtures. Fig. 3.9 shows the accessories used for California Bearing Ratio test. A mould of 150 mm in diameter and 175 mm height with a detachable collar of 50 mm height and a detachable perforated base plate was used. Firstly, a displacer disc of 50 mm height was placed in the mould. The wet mixture of clayey soil-cement-rubber crumbles/fibres was put into mould in five layers. Each layer of mixture in the mould was compacted by 56 blows of rammer weighed 4.89 kg dropped from a height of 450 mm above the mixture (Fig. 3.10(a)). Then the collar was removed, and the excess mix was trimmed off. The mould was then turned upside down and base plate, and displacer disc was removed. For soaked conditions, a filter paper at top and bottom was placed. A perforated plate on the top of filter paper with a surcharge load of 5 kg was placed, and the specimen was immersed in water for a duration of 96 hours' prior of testing (Fig. 3.10(b)).

Fig. 3.9 Accessories for California bearing ratio test

Fig. 3.10(a) Sample preparation of California bearing ratio test, **(b)** specimens soaked under water

3.5.3 Sample preparation for One-dimensional consolidation and Swelling Pressure Tests

For conducting the one-dimensional consolidation and swelling pressure tests, each sample was prepared at their maximum dry unit weight and optimum moisture. The compacted samples were extracted from the mould by using sample extractor (Fig. 3.11(b)). Then, the specimens of 60 mm diameter and 20 mm height were extruded with the help cutting ring (Fig. 3.11(c)-(d)). The specimens so obtained were cured for 28 days in the humidity controlled room at temperature of 25°C and humidity 96% before testing. 28 days cured specimen was placed in consolidation cell with fitter paper and porous stone at the top and bottom (Fig. 3.11(e)-(l)). Then the mould assembly was mounted on the loading frame, and then load was applied axially.

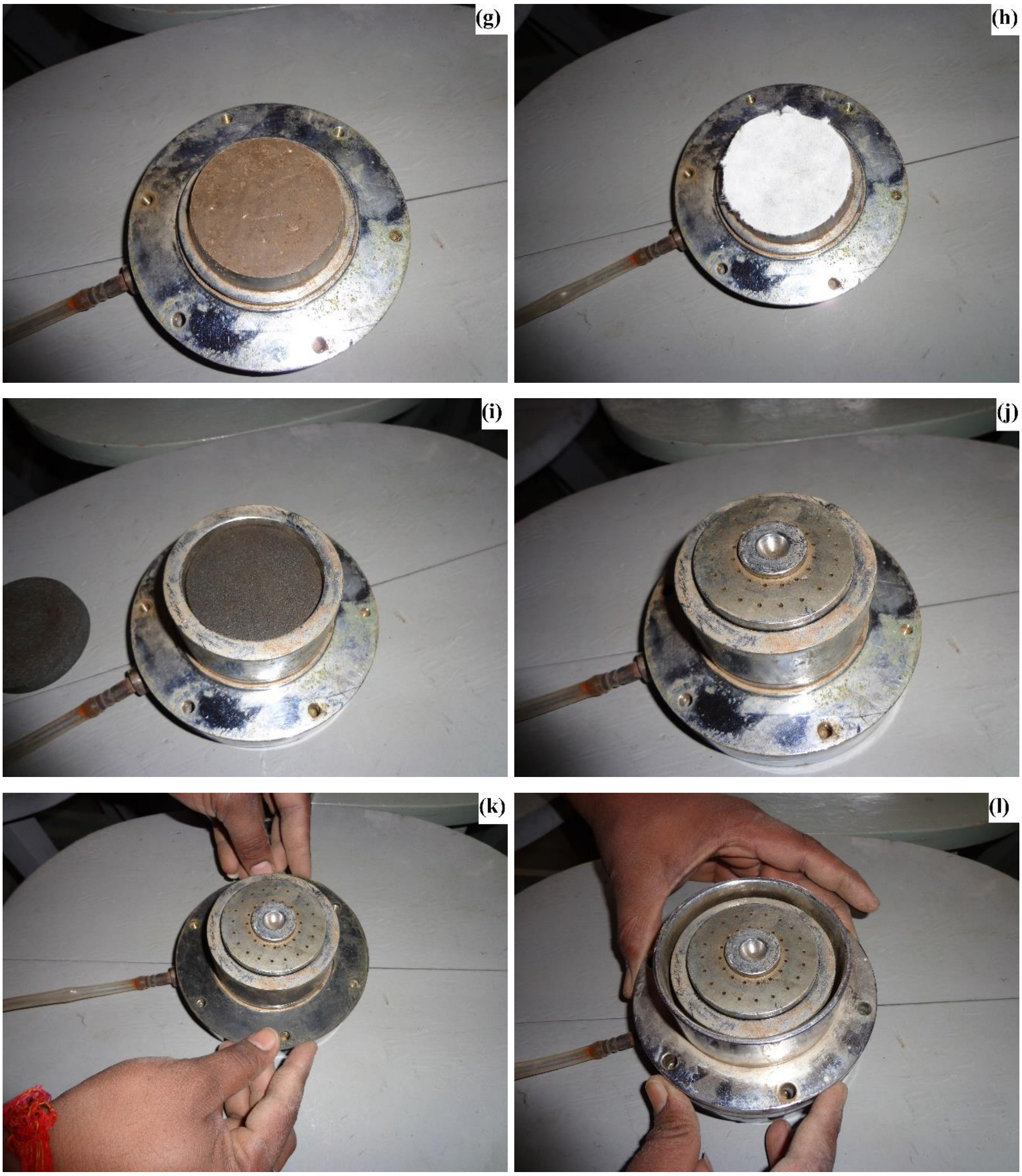


Fig. 3.11 Sequential steps for sample preparation for one dimensional consolidation and swelling pressure testing from: (a) to (l)

3.5.4 Sample preparation for Durability Tests

In Figure 3.12, the photographs of various stages of sample preparation for clayey soil-cement-rubber crumbles/fibres mixtures for wet/dry durability testing are given. Cylindrical specimens of 100 mm diameter and 127.3 mm height were prepared for different mixtures at their respective maximum dry unit weight and optimum moisture content and extracted from the mould by using sample extractor as shown in Fig. 3.12(a) - 3.12(f). The samples so obtained were wrapped in the plastic sheet Fig. 3.12(g) and placed in humidity control room for curing period of 7, 28, 90, and 180 days (as revealed in Fig. 3.12(h)).

Fig. 3.12 Sequential steps for sample preparation for wet/dry durability testing from: (a) to (h)

3.6 TESTING PROGRAM

The impact of waste rubber crumbles/fibres inclusion on geotechnical properties of cement stabilized clayey soil were assessed using different tests; namely, compaction, unconfined compressive strength, split tensile strength, California Bearing Ratio (CBR), one-dimensional consolidation, swelling pressure and wet/dry durability tests. The mineralogical and microscopical studies of mixtures were carried out to get the better intuition of mixtures. The relation between dependent variable and independent variables for all performed tests was also established by using multiple linear regression analysis (MLRA). For this purpose, statistical software SPSS 12.0 was used. Table 3.10 shows the various tests conducted and relevant codes of practice adopted. This section describes standard methodologies adopted for the tests.

Table 3.10 Tests conducted and relevant codes of particle

Tests	Code used
Modified Proctor compaction test	IS: 2720 (Part VIII-1983)
Unconfined compressive strength test	IS : 2720 (Part X-1991)
Split tensile strength test	ASTM C 496-96
California bearing ratio test	IS: 2720 (Part XVI-1987)
One-dimensional consolidation test	IS: 2720 (Part XV)-1965
Swelling pressure test	IS: 2720 (Part 41-1977)
Wet/dry durability test	IS : 4332 (Part IV-1968)

3.6.1 Compaction Test

The moisture content and dry unit weight relationship play a key role on the geotechnical behaviour of soil. Modified Proctor compaction tests were conducted on the various combinations of clayey soil-cement-rubber crumbles/fibres as shown in Table 3.7 and 3.8 to determine their maximum dry unit weight and optimum moisture content. The standard methodology mentioned in IS: 2720 (Part VIII-1983) was adopted. Clayey soil, cement and rubber crumbles/fibres were mixed thoroughly in dry condition. Then, the selected water content was added, and mixture was again thoroughly mixed. The wet mixture of soil-cement-rubber crumbles/fibres was placed into a standard mould of 1000 cm^3 capacity in five layers. Each layer of mixture in the mould was compacted by 25 blows of rammer weighed 4.9 kg dropped from a height of 450 mm above the mixture as shown in Fig. 3.13. The compaction of each stabilized soil sample was completed within 20 minutes. The compacted mix was then weighed, and sample was taken for moisture measurement. This process was replicated for five percentages of water content. The moisture content (post-compaction water content) was measured by drying the sample of mixture in the oven. From the dry unit weight and water content, data compaction curves were plotted for each combination and maximum dry unit weight and optimum moisture content were determined. The specimens of tests namely, unconfined compressive strength, split tensile strength, CBR, one-dimensional consolidation, swelling pressure, and wet/dry durability were prepared with reference to maximum dry unit weight and optimum moisture content of the individual mixture. The results of this test are useful in evaluating the application of proposed composite as fill material and stability of field problems like earthen dams, embankments, roads, airfields, etc.

Fig.3.13 Modified Proctor compaction test apparatus

3.6.2 Unconfined Compressive Strength Test

The unconfined compression strength test is used as an indicator of the structural stability of cement stabilized clayey soil containing rubber crumbles and in different engineering applications. Unconfined Compressive Strength test was performed on the various combinations of soil-cement-rubber crumbles/fibre as described in Table 3.7 and 3.8 in agreement with the guidelines of IS : 2720 (Part X-1991).The specimens of unconfined compressive strength tests were prepared as per the procedure mentioned in section 3.5.1. For testing, the specimen was placed axially between the two bearing plates of compressive strength measurement machine. The load was applied to samples by using the load frame and proving ring of 2 kN at the axial strain rate of 1.25 mm/min. The unconfined compressive strength of specimen was calculated from the following equation:

$$q_u = \frac{Pu}{A} \tag{3.6}$$

where q_u = Unconfined compressive strength; Pu = Axial load corresponding to failure and A = A_0/ (1-ε); A =corrected area, A_0 = Initial cross sectional area, ε = ΔL/L, ΔL = change in length of specimen and L = initial length of the specimen. A view of the unconfined compressive strength is shown in Fig 3.14. The details of specimens tested for unconfined compressive strength test are given in Table 3.11.

Fig. 3.14 Unconfined compression test apparatus

Table 3.11 Detail of specimens tested under unconfined compressive strength test

Details of experiments	No. of specimens tested
Specimens of soil-cement mixture containing 0%, 3%, and 6% cement cured for 7, 14, 28 days **(unsoaked + soaked)**	27 + 27
Specimens of soil-cement-rubber crumble/fibre mixture containing 0%, 3%, and 6% cement and 2.5%, 5%, 7.5%, and 10% rubber crumble/fibre cured for 7, 14, 28 days **(unsoaked + soaked)**	(108 + 108) x 2*****

*****Specimens with rubber crumbles and rubber fibres

3.6.3 Split Tensile Strength Test

The tensile stresses are induced in earth structures due to the movement of vehicles, reduction in volume due to shrinkage, alternate drying and wetting of soils, thermal stresses due to seasonal variation in temperature. For determination of tensile strength of soils various tests like direct tensile test, split-cylinder test (split tensile strength test), bending test, and double punch tensile test are used. In the present investigation, the split tensile strength test of the composite was calculated according to the formula mentioned in ASTM C 496-96. Many researchers in the past had used the same formula for the determination of split tensile strength of soil mixes. (Sobhan and Mashnad, 2002; Cokca and Yilmaz, 2003; Kumar et al., 2007; Fatahi. B et al., 2013 ; Kumar and Gupta, 2016 ; Baldovino et al., 2018 ; Trani et al., 2018). The specimen of split tensile strength tests were prepared as per the procedure mentioned in section 3.5.1. The proving ring of capacity 2 kN was used. The strain rate was kept 1.25 mm/min in all the experiments. The specimens of standard dimensions were kept between the plates of machine for finding the tensile strength under radial compression. During the test, a uniform bearing pressure was maintained. For, this purpose, the mild steel strips of curved shape were kept on the contact surface of specimens. A 10 mm wide and 76.2 mm long metal strip having thickness 5 mm was used. Many researchers in the past had used the same methodology for the determination of split tensile strength of the soil. (Sobhan and Mashnad, 2002; Cokca and Yilmaz, 2003; Kumar et al., 2007; Fatahi. B et al., 2013 ; Kumar and Gupta, 2016 ; Baldovino et al., 2018 ; Tran et al., 2018). A schematic sketch of a specimen for the split tensile test is shown in Fig. 3.15(a). Three specimens of each combination were prepared and tested. The split tensile strength of the specimen was calculated by using the following equation:

$$q_s = \frac{2P}{\pi t d} \tag{3.7}$$

where q_s= Split tensile strength; P= Tensile load corresponding to Failure; t= Thickness or length of specimen; and d= diameter of the specimen. A view of the split tensile strength apparatus is shown in Fig. 3.15(b). The details of specimens tested for split tensile strength test are given in Table 3.12. Three identical specimens of each combination were prepared and tested to minimize the error due to materials and test conditions.

Table 3.12 Detail of specimens tested under split tensile strength test

Details of experiments	No. of specimens tested
Specimens of soil-cement mixture containing 0%, 3%, and 6% cement cured for 7, 14, 28 days **(unsoaked + soaked)**	27 + 27
Specimens of soil-cement-rubber crumble/fibre mixture containing 0%, 3%, and 6% cement and 2.5%, 5%, 7.5%, and 10% rubber crumble/fibre cured for 7, 14, 28 days **(unsoaked + soaked)**	(108 + 108) x 2*

*Specimens with rubber crumbles and rubber fibres

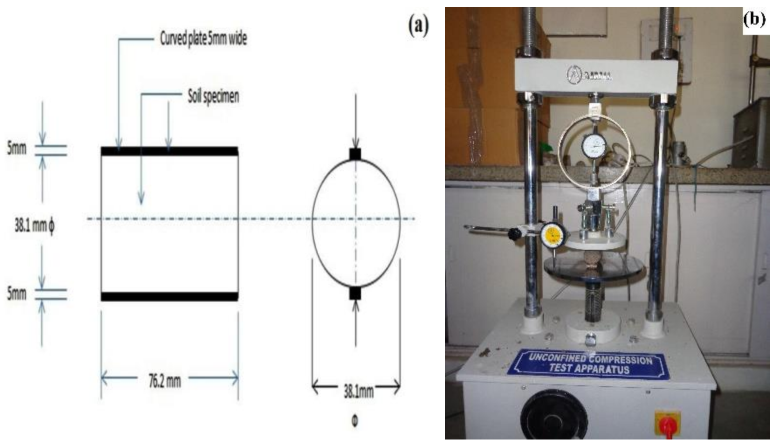


Fig. 3.15(a) Schematic sketch of specimen for split tensile test, **(b)** Split tensile strength test apparatus

3.6.4 California Bearing Ratio Test

The quality and life of the pavement are greatly affected by the type and quality of the subgrade soil. It should have high compressive and shear strength, ease of drainage and low susceptibility to volume changes in all weather conditions. California bearing ratio (CBR) tests on clayey soil with and without rubber and cement content for both unsoaked and soaked conditions were carried out as per the guidelines prescribed in IS: 2720 (Part XVI)-1987.The specimens of California Bearing Ratio tests were prepared as per the procedure mentioned in section 3.5.2. The proving ring of capacity 5kN was used for the testing. The load was applied on the specimen through penetration piston at rate of 1.25 mm/min and load readings were recorded at penetrations, 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 7.5, 10, and 12.5 mm. The CBR (%) of specimens were obtained by dividing the loads corresponding to 2.5 mm and 5.0 mm penetration to the standard loads of 1370 kg and 2055 kg, respectively.

Fig. 3.16 California Bearing Ratio test apparatus

A view of the California Bearing Ratio apparatus is shown in Fig. 3.16. The details of specimens tested for California Bearing Ratio test are given in Table 3.13.

Table 3.13 Detail of specimens tested under California bearing ratio test

Details of experiments	**No. of specimens tested**
Specimens of soil-cement mixture containing 0%, 3%, and 6% cement **(unsoaked + soaked)**	(12 + 12)
Specimens of soil-cement-rubber crumbles/fibre mixture containing 0%, 3%, and 6% cement and 2.5%, 5%, 7.5%, and 10% rubber crumbles/fibre **(unsoaked + soaked)**	(24 + 24) x 2*****

***** Specimens with rubber crumble and rubber fibre

3.6.5 One-dimensional Consolidation Test

One-dimensional consolidation tests were conducted to obtain the compression index of cemented clay-rubber mixture specimens according to IS: 2720 (Part XV)-1965. The specimen of one-dimensional consolidation tests was prepared as per the procedure mentioned in section 3.5.3. Before applying the normal stresses, the specimens were allowed to saturate. During the test, water was added into the cell around the sample, so the sample remains saturated during the test. A small reservoir located at certain height was used to add the water into consolidation cell. The cell had a provision of allowing water to flow through soils specimen under certain nominal head. The two porous stones at the top and bottom of the sample allow a two-way drainage of the sample. The soil sample was assumed to be 100% saturated, when the expulsion of water starts from the outlet point of the cell. The rate of addition of water into the consolidation cell and outlet was kept constant and controlled by stopper. The sample was allowed to reach equilibrium for 24 hrs. After the saturation of specimen, the normal stresses of range 12 kPa, 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, and 800 kPa, respectively were applied to obtain vertical strain- log σ' plot. The successive stress changes were applied after the duration of 24 hrs. The vertical deformation-log σ curves of mixtures were obtained, and compression indices of the mixtures were calculated. The rate and amount of settlement of structure founded on clay primarily due to the volume change of clay can be obtained by consolidation test.

The compression index, C_C is an indication of the compressibility of any soil. To calculate the compression index, two point are selected along a linear section of the curve. The point possesses void ratio e_1 and e_2, and stress σ_1' and σ_2'respectively are selected so that $e_1 > e_2$ and $\sigma_2' > \sigma_1'$. Compression index is then expressed as

$$C_C = \frac{e_1 - e_2}{\log \sigma_2' - \log \sigma_1'} \tag{3.8}$$

In this investigation only the loading stage of the consolidation test on the clayey soil-cement-rubber crumbles/fibres mixtures were carried out. The unloading stage with pressure decrements of one fourth of the last load was not carried out in this investigation. The unloading and reloading portion of the consolidation test could not be conducted to due to time and other constraints. In this investigation, 54 combinations of clayey soil-cement-rubber crumbles/fibres were tested for the consolidation characteristics.

A view of one-dimensional consolidation test is shown in Fig. 3.17. The details of specimens tested for one-dimensional consolidation test are given in Table 3.14.

Fig. 3.17 One-dimensional consolidation test apparatus

Table 3.14 Detail of specimens tested under One-dimensional consolidation test

Details of experiments	**No. of specimens tested**
Specimens of soil-cement mixture containing 0%, 3%, and 6% cement	6
Specimens of soil-cement-rubber crumbles/fibre mixture containing 0%, 3%, and 6% cement and 2.5%, 5%, 7.5%, and 10% rubber crumbles/fibre	(24) x 2*****

***** Specimens with rubber crumbles and rubber fibres

3.6.6 Swelling Pressure Test

IS: 2720 (Part 41-1977) standard specifications were followed for assessing the impact of rubber crumbles/fibres and cement inclusion on the swelling pressure of clayey soil. The specimens of swelling pressure tests were prepared as per the procedure mentioned in section 3.5.3. The swelling pressure of specimens was evaluated by using constant volume method. For this test, specimens were prepared at their maximum dry density and optimum water content. After placing the sample in the consolidation ring, the specimens were inundated with water and swelling was observed simultaneously. As the specimen started to swell, a small pressure increment was applied to prevent swelling and maintain the initial volume as constant. At some point, the specimen had no further tendency to swell under the applied load. This applied pressure was recorded as the swell pressure of the specimen. The swelling pressure of soil can be used to develop estimates of heave or settlement for given moisture and loading conditions, which plays an important role in the design of floor slabs. The details of specimens tested for swelling pressure test are given in Table 3.15

Table 3.15 Detail of specimens tested for swelling pressure test

Details of experiments	No. of specimens tested
Specimens of soil-cement mixture containing 0%, 3%, and 6% cement	6
Specimens of soil-cement-rubber crumble/fibre mixture containing 0%, 3%, and 6% cement and 2.5%, 5%, 7.5%, and 10% rubber crumbles/fibre	(24) x 2*

* Specimens with rubber crumbles and rubber fibres

3.6.7 Durability Test

The most crucial parameter to assess the suitability of any construction material is its durability. The durability of cement - stabilized soils can be predicted by tube suction, 7-day unconfined compression strength, wetting - drying cycles and freezing–thawing cycle’s tests. In this investigation, the traditional wetting - drying cycles tests were performed in conformity with IS : 4332 (Part IV-1968)to securing the durability of the proposed composite in the adverse environmental conditions. The specimen of durability tests was prepared as per the procedure mentioned in section 3.5.4. After the completion of curing age, the specimens were exposed to twelve alternate wetting and drying cycles. Each wetting and dry cycle consisted of 5 hours of soaking in potable water at room temperature (as illustrated in Fig. 3.18(a)) and 42 hours of heating in an oven at 70 ^{0}C (as shown in Fig. 3.18(b)). After that, the specimens were subjected to a defined number of firm strokes of wire scratch brush parallel to the longitudinal axis of specimens at approximately 14 N force along the height and diameter. The weight loss upon scratching after each wet and dry cycle was then recorded. The details of specimens tested for wet/dry durability test are given in Table 3.16.

According to Portland Cement Association (PCA) and Bhattacharja and Bhatty (2003), the weight loss of the specimens after 12 cycles of wetting and drying should not exceed 14% for granular soils of low plasticity and 7% for cohesive clays of their original mass. However, these recommendations of PCA were found to be too stringent as per some other studies (IRC: SP:89 (2010). 20% and 30% loss in mass have been recommended for the cement stabilized materials to be used as the base, sub-base, and shoulder for the construction of roads as per IRC: SP: 89-2010.

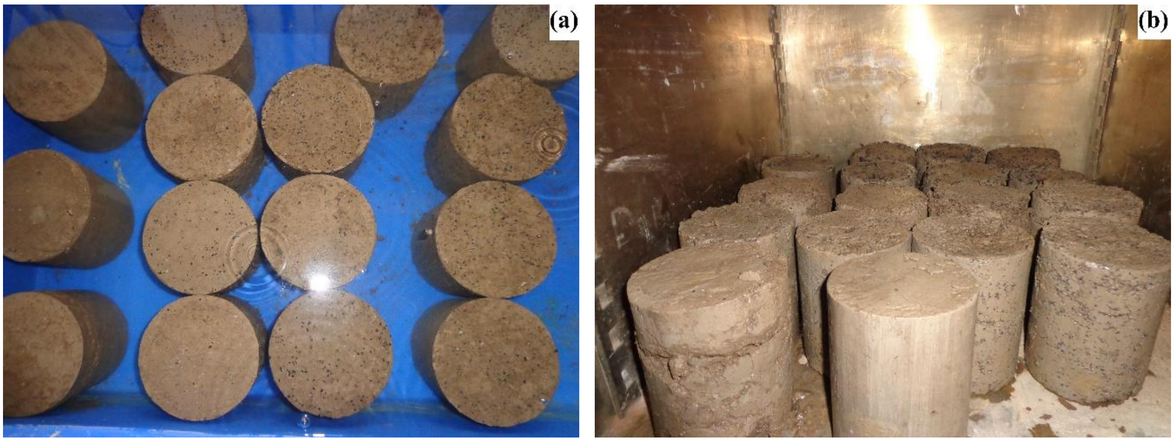


Fig. 3.18 Specimens under durability tests **(a)** Wetting cycle, **(b)** Drying cycle

Table 3.16 Detail of specimens tested under durability test

Details of experiments	**No. of specimens tested**
Specimens of soil-cement mixture containing 0%, 3%, and 6% cement cured for 7, 28, 90, and 180 days	24
Specimens of soil-cement-rubber crumbles/fibre mixture containing 0%, 3%, and 6% cement and 2.5%, 5%, 7.5%, and 10% rubber crumbles/fibre cured for 7, 28, 90, and 180 days	(96) x 2*

***** Specimens with rubber crumbles and rubber fibres

3.6.8 Microscopy and Morphological Test

The most probable phases of mineral present in specimens after curing were determined by the X-ray diffraction studies. A PANalytical X'pert PRO Powder diffractometer (Type 11141934) having copper electrodes that act as the source of radiation (Cu-Kά radiation, 40 kV- 40 mA) was used. The specimens were scanned from 2θ = 10.020 to 79.9800 with step scanning at 0.02°/0.5 s. X'pert High score equipped with JCPDS PDF-2 database (ICDD 2003) was used to identify the mineralogical phases present in the mixtures.

The morphology of mixes was assessed by using Navo Nano FE-SEM450 (Field emission gun scanning electron microscope). Testing was conducted on 1cm×1cm cut pieces obtained from 28 days cured specimens. The cut pieces were coated with platinum in sputter coating equipment, which prevents the specimen from charge accumulation during the experiment. FE-SEM focused a beam of primary electron on the specimen and gave a view of its topography by absorbing primary electron beam and reflecting secondary electron. SEM images of specimens were analyzed for the better understanding of behaviour of the mixture.

3.7 CONCLUDING REMARKS

The test results of compaction, unconfined compressive strength, split tensile strength, California Bearing Ratio, one-dimensional consolidation, swelling pressure, and durability along with the microscopical and morphological tests of different combinations of clayey soil-cement-rubber crumbles/fibres have been presented and discussed in detail in the following Chapter 4, 5, and 6.

CHAPTER 4

INFLUENCE OF WASTE RUBBER CRUMBLES/FIBRES ON THE GEOTECHNICAL PROPERTIES OF CLAYEY SOIL

4.1 GENERAL

The environmental friendly and safe disposal of waste discarded rubber tires are becoming a matter of serious concern across the globe because of its detrimental effect on health, environment, and ecological systems. This chapter presents the impact of waste rubber tire inclusion on compaction, unconfined compressive strength, split tensile strength, California Bearing Ratio, one-dimensional consolidation, swelling pressure, durability and microstructure of clayey soil. It may be recalled that the rubber crumbles/fibres with content varying from 0 to 10% were mixed in the clayey soil.

4.2 COMPACTION STUDIES

The maximum dry unit weight and optimum moisture content of all the clayey soil-rubber crumbles and clayey soil-rubber fibres mixtures were determined from modified Proctor test. The compaction curves of different clayey soil-rubber crumbles and clayey soil-rubber fibres mixtures are shown in Figs. 4.1 and 4.2, respectively. Figs. 4.3 and 4.4 show the maximum dry unit weight and optimum moisture content of clay-rubber crumbles/fibres mixtures.

The maximum dry unit weight and optimum moisture content of clayey soil are 16.3 kN/m^3 and 20.9%, respectively as shown in Fig. 4.3. A study of Fig. 4.3 reveals that as the rubber crumbles content increases, the maximum dry unit weight and optimum moisture content of clay decreases. For example, the maximum dry unit weight and optimum moisture content of mix $S_{97.5}C_0Rc_{2.5}$ was 16.1 kN/m^3 and 20.3%, which reduced to 14.5 kN/m^3 and 18.8%, respectively for the mix $S_{90}C_0Rc_{10}$. Similarly, as the rubber fibres content increases in clayey soil, the maximum dry unit weight and optimum moisture content of clayey soil decreases as shown in Fig. 4.4. The addition of 2.5%, 5%, 7.5%, and10% rubber fibres reduces the maximum dry unit weight of clayey soil from 16.3 kN/m^3 to 16.2kN/m^3, 15.6 kN/m^3, 15 kN/m^3, and 14.8 kN/m^3, respectively.

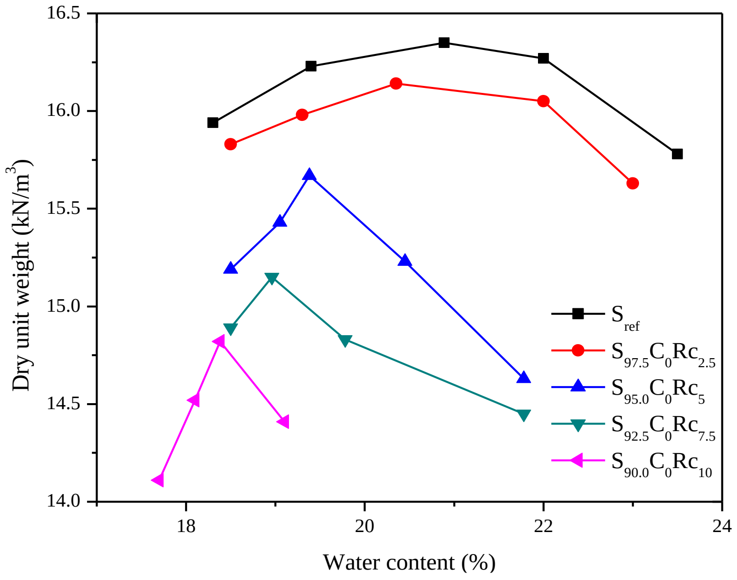


Fig. 4.1 Compaction curves of the clayey soil-rubber crumbles mixtures

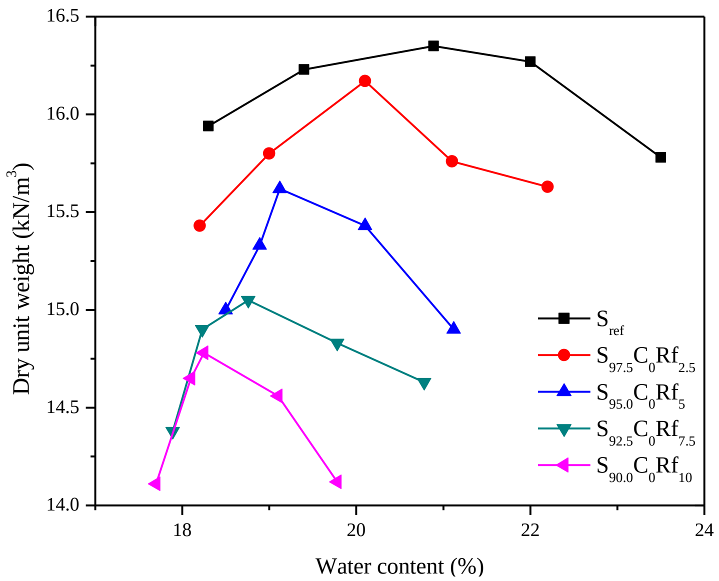


Fig. 4.2 Compaction curves of the clayey soil-rubber fibres mixtures

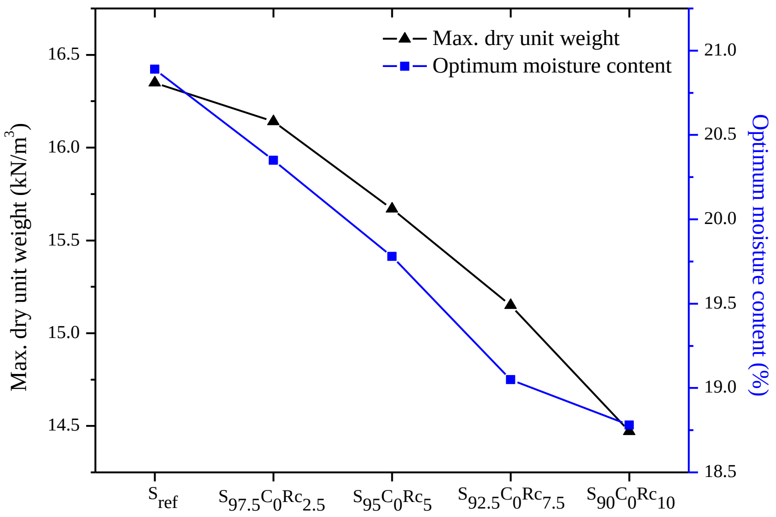


Fig.4.3 Maximum dry unit weight and optimum moisture content of the clayey soil-rubber crumbles mixtures

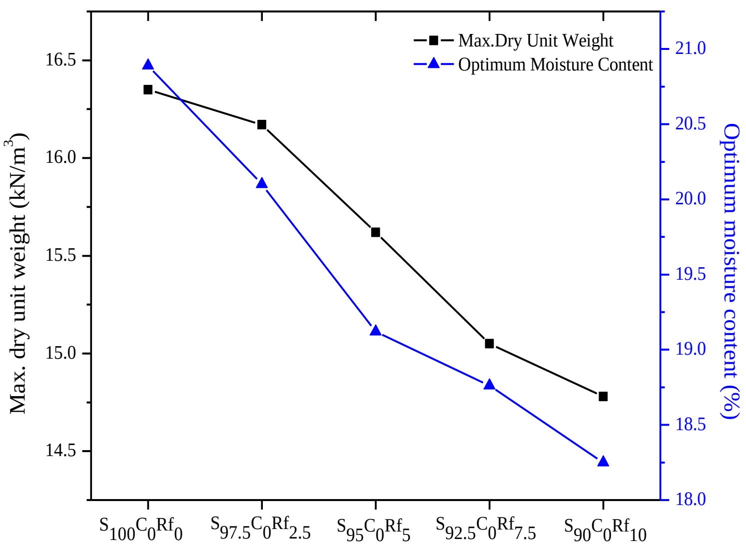


Fig.4.4 Maximum dry unit weight and optimum moisture content of the clayey soil-rubber fibres mixtures

The specific gravity of clayey soil, rubber crumbles, and rubber fibres is 2.69, 1.13, and 1.07, respectively. The specific gravity of rubber crumbles/fibres is quite lower than specific gravity of natural soil. The decrease in maximum dry unit weight may be attributed to the low specific gravity of rubber crumbles/fibres as compare to clayey soil and loss of compaction efficiency due to the elastic response or resilience of rubber during compaction. During the compaction, a rebound of the rammer was observed with increase in the percentage of rubber content in the mix. Apart from that, the segregation of rubber particles from rest of the composite was also observed at high percentages of rubber content. Keeping these observations in view, the static compaction would be better for field application of the proposed composite. However, experimental investigation should be carried out first to confirm the same. The decrease in optimum moisture content of clay with incorporation of rubber crumbles/fibres may be possible due to low water absorption capacity of rubber particles.

This trend of maximum dry unit weight and optimum moisture content reduction was consistent with the results reported by other investigators (Kalkan, 2013;Srivastava et al., 2014; Cabalar et al., 2014; Signes et al., 2016). But the variation of optimum moisture content of clay with incorporation of rubber crumbles/fibres were found contrary to the results reported by Al-Tabbaa et al., (1997), Al-Tabbaa and Aravinthan (1998), and Seda et al., (2007). Al-Tabbaa and Aravinthan (1998)had shown in their investigation that the optimum moisture content of the clay remains unchanged with the increase in content of rubber. They observed 'good bonding' between the tire and clay particles of compacted samples and was cited as a reason for the increase in moisture content. This difference in the response of the composite could be due to not only difference in type of clay, but also due to difference in rubber waste type, size and content, and other additives, as well used by various researchers.

4.3 UNCONFINED COMPRESSION BEHAVIOUR

4.3.1 Axial Load-Deformation response

The axial load-deformation response of clayey soil incorporated with 2.5%, 5%, 7.5%, and 10% rubber crumbles/rubber fibres are shown in Figs. 4.5 and 4.6. A study of Fig. 4.5 reveals that the peak axial load of clayey soil mixed with varying rubber crumbles content increases marginally with the increase in rubber content up to 5%. For example, the peak axial load of specimen S_{ref} was 0.0739 kN, which increased to 0.0749 kN and 0.0772 kN, for specimen $S_{97.5}C_0Rc_{2.5}$ and $S_{95}C_0Rc_5$, respectively. A further inclusion of rubber crumbles decreases the peak axial load of clay- rubber crumbles mixtures. These results are in agreement with previous study carried out by Srivastava et al. (2014) on black cotton soil mixed with shredded tyre waste.

It can be inferred from Fig. 4.6 that the axial load of clayey soil specimen increases marginally from 0.0734 kN to 0.07651 kN with the addition of 2.5% rubber fibres content. Further incorporation of rubber fibres reduces the peak axial load of clay. When the rubber fibre content was increased from 7.5% to 10%, the peak axial load decreased by 12.30% and 21.71%, respectively as compared to clayey soil. The reduction of peak axial load at 7.5% and 10% rubber fibre content may be due to increase in interaction between the rubber fibres and accumulation of rubber fibres (Cabalar et al., 2014; Tajdini et al., 2016).

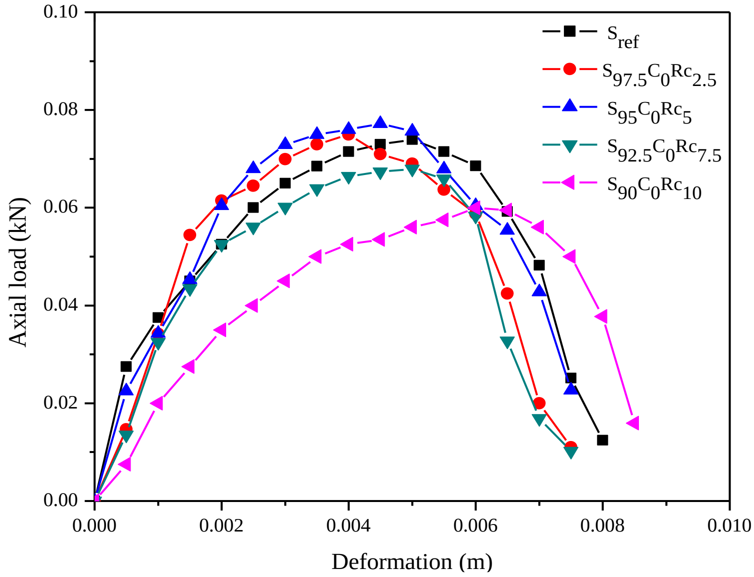


Fig. 4.5 Axial load- Deformation of clayey soil mixed with rubber crumbles

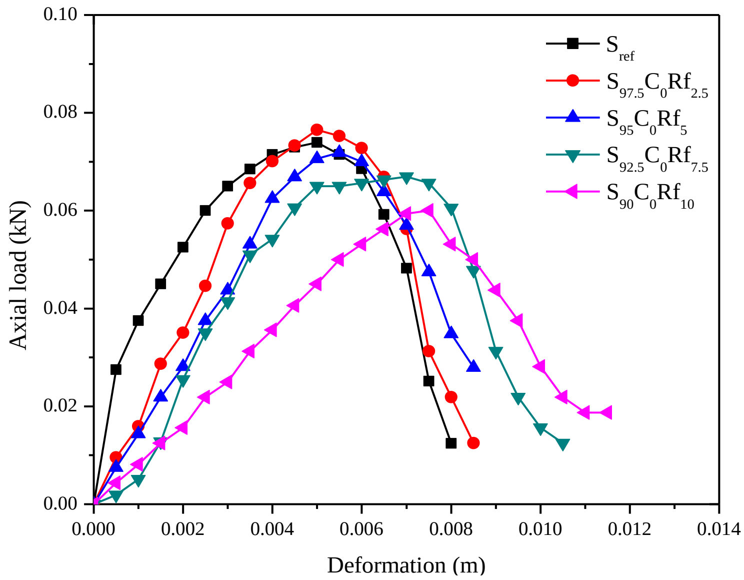


Fig. 4.6 Axial load- Deformation of clayey soil mixed with rubber fibres

Figs. 4.5 and 4.6 reveal that the deformation at failure of clayey soil increases with the inclusion of rubber crumbles and rubber fibres. For example, for the specimen of clayey soil containing 2.5% rubber crumbles, the deformation at failure was 0.0040 m, which increased to 0.0045 m,0.0050 m, and 0.006 m for 5%, 7.5%, and 10% incorporation, respectively. Similarly, the deformation at failure of clayey soil containing 2.5% rubber fibres was 0.005

m, which increased to 0.0055 m, 0.007 m, and 0.0075 m, for clayey soil containing 5%, 7.5%, and 10% rubber fibres, respectively. The increase in deformation at failure of clayey soil containing rubber crumbles and rubber fibres may be accredited to (i) resilient behavior of the rubber crumbles(Tajdini et al. 2016), (ii) elastic reaction generated by the rubber particles during compression, results into prevention against generation of cracks(Yoshio et al. 2008). The elastic compression of rubber crumbles/fibres results into strain hardening of the clay after reaching the peak axial load.

The addition of rubber crumbles/fibres reduces the rate of post-peak strength loss, which ultimately improves the ductility of soil. Although, the specimen $S_{97.5}C_0Rc_{2.5}$, $S_{95}C_0Rc_5$, and $S_{97.5}C_0Rc_{7.5}$ have shown strain-softening behaviour. Similarly, the clayey soil containing 2.5% and 5% rubber fibres shows strain-softening behaviour with a significant rate of loss of post-peak load.

4.3.2 Absolute toughness in compression

Absolute toughness, an indicator of the total energy absorption capacity of composite has been determined by calculating the area of axial load-deformation curve upto failure as shown in Fig. 4.7. The results of absolute toughness of clayey soil incorporated with 2.5%, 5%, 7.5%, and 10% rubber crumbles and rubber fibres is shown in Fig. 4.8.

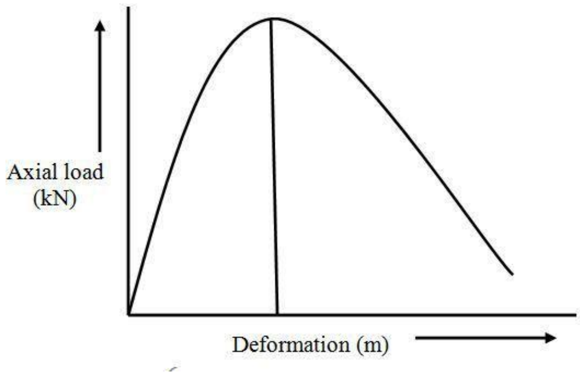


Fig. 4.7 Schematic diagram for absolute toughness

A study of Fig. 4.8 reveals an increase in the absolute toughness of clayey soil with inclusion of rubber crumbles up to 5%. For example, the absolute toughness of specimen S_{ref} was 0.000246 kN.m, which increased to 0.000268 kN.m, when 5% rubber crumbles were incorporated. Further inclusion of rubber crumbles reduced the absolute toughness of clayey soil slightly. For example, the absolute toughness of specimen S_{ref} reduced to 0.000244 kN.m and 0.000237 kN.m when 7.5% and 10% rubber crumbles were incorporated. Similarly, an increase in the absolute toughness of clayey soil was observed with the inclusion of rubber fibres up to 7.5%. For example, the absolute toughness of specimen S_{ref} was 0.000246 kN.m, which increased to 0.000291 kN.m, when 7.5% rubber fibres were incorporated. Further inclusion of rubber fibres reduced the absolute toughness of clayey soil. However, the value of toughness index of clayey soil containing 10% rubber crumbles and rubber fibres was found comparable to clayey soil. Sobhan and Mashnad (2002) had also evaluated the absolute toughness of soil – cement – fly ash composite reinforced with recycled high density polythene strips.

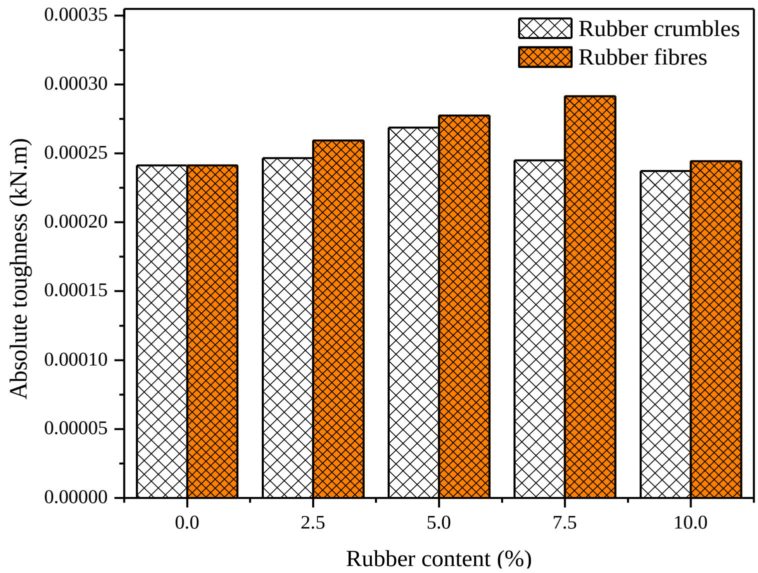


Fig. 4.8 Absolute toughness of clayey soil mixed with rubber crumbles and rubber fibres

4.3.3 Post peak Compression Response

For better understanding of clay- rubber crumbles/fibres mixtures in post peak region, the normalization of load and deformation axis of axial load-deformation curves was done with respect to the peak axial load (denominated as Pp) and deformation corresponding to peak axial load (denominated as dp). The variation of normalized load with normalized deformation of clayey soil containing rubber crumbles and rubber fibres are shown in Figs. 4.9 and 4.10, respectively. Study of Fig. 4.9 clearly shows a sharp drop in the post-peak axial load of specimen S_{ref}. Similarly, specimens $S_{97.5}C_0Rc_{2.5}$ and $S_{95}C_0Rc_5$ show sharp drop in the post-peak axial load, which is an indication strain-softening behaviour of the mixture. A similar behaviour of the specimens of clayey soil incorporated with 2.5%, and 5% rubber fibres was noticed. Contrary to this specimens $S_{92.5}C_0Rc_{7.5}$ and $S_{90}C_0Rc_{10}$ was observed to follow a gradual decline after the attainment of peak in normalized load-deformation curves, which is an indicative of the strain hardening behaviour and change of behaviour from brittle to ductile. The specimens $S_{92.5}C_0Rf_{7.5}$ and $S_{90}C_0Rf_{10}$ also show gradual decline after the attainment of peak as shown in Fig. 4.10. The rubber crumbles and rubber fibres have elastic nature, which prevents generation of crack may be possible reason for the change in behaviour of the composite from brittle to ductile.

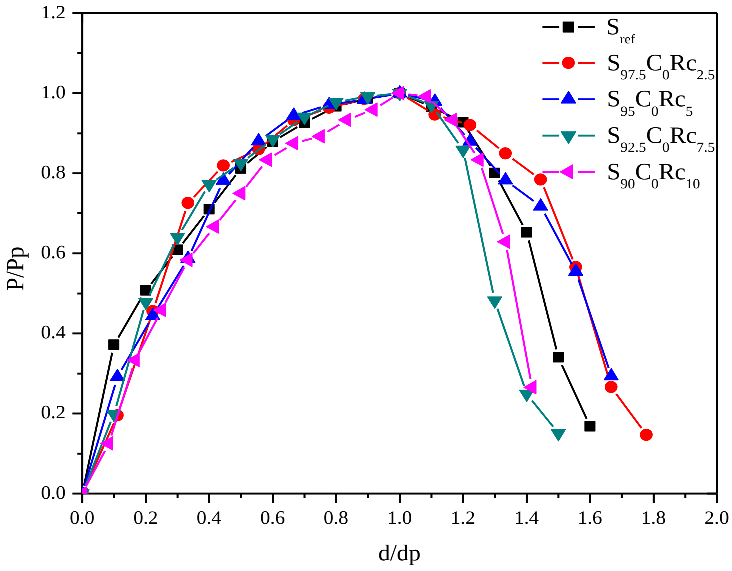


Fig. 4.9 Normalized axial load- deformation of clayey soil mixed with rubber crumbles

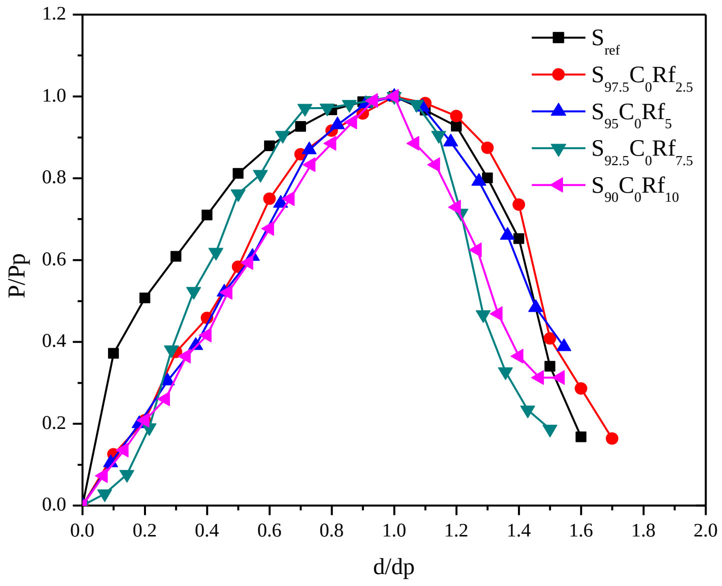


Fig. 4.10 Normalized axial load- deformation of clayey soil mixedwith rubber fibres

4.3.4 Toughness Index in unconfined compression

Toughness index (TI) is defined by Sobhan and Mashnad (2002) as:

$$TI = \frac{Ad - Ap}{(d/dp - 1)} \qquad (4.1)$$

Where

dp= deformation at peak axial load Pp.

d= any deformation that is greater than dp value.

Ap= area under the normalized curve upto peak.

Ad= area under the normalized curve upto the deformation ratio d/dp.

The TI value calculated in this way compares the performance of a specimen with that of an elastic–perfectly plastic reference material, for which the TI is unity for any value of deformation ratio. On the other hand, TI is zero for an ideal brittle material with no post peak load carrying capacity. Although, the toughness index of the composite is not used in directly anywhere in geotechnical design but it is an indicator of brittle and elastic-perfectly behavior of the material.

Fig. 4.11 shows the average value of toughness index of clayey soil containing rubber crumbles and rubber fibres. It can be seen from Fig. 4.11 that the toughness index of clayey soil increases with the incorporation of rubber crumbles content up to 5%. For example, for specimens S_{ref}, the toughness index was 0.7118, which increased to 0.7601 with the addition of 5% rubber crumbles. Further incorporation of rubber crumble reduces the toughness index. For example, the inclusion of 7.5% and 10% rubber crumbles reduced the toughness index of clayey soil from 0.7601 to 0.7353 and 0.7040, respectively. Study of Fig. 4.11 reveals an increase in the toughness index of clayey soil with the addition of rubber fibres content up to 7.5%. For example, for specimen $S_{97.5}C_0Rf_{2.5}$, the value of TI was 0.6986, which increased to 0.7229 and 0.7588, respectively, for specimen $S_{95}C_0Rf_5$, and $S_{92.5}C_0Rf_{7.5}$. Further incorporation of rubber fibres reduces the toughness index of clayey soil.

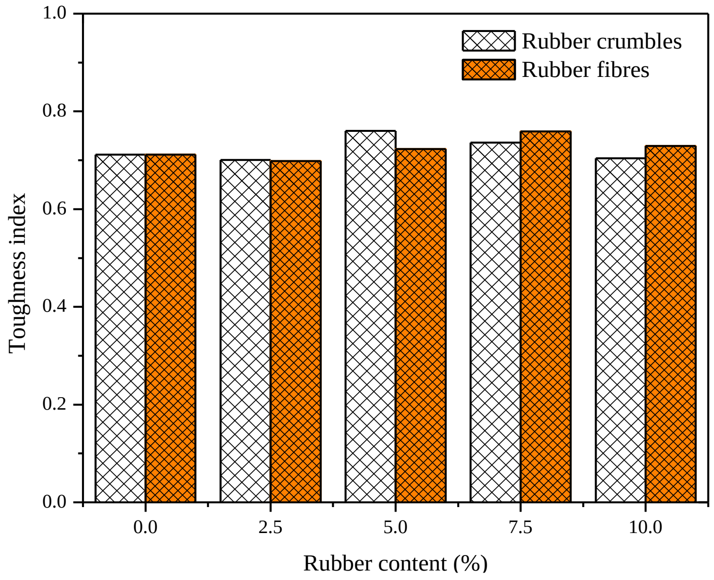


Fig. 4.11 Toughness index of clayey soil mixed with rubber crumbles and rubber fibres

4.3.5 Pattern of cracking in compression

Figs. 4.12(a) to 4.12(e) show the typical failure patterns of clayey soil specimens containing 2.5%, 5%, 7.5%, and 10% rubber crumbles. The clayey soil specimen fails along the shear plane, which appears from the top to bottom as shown in Fig. 4.12(a) indicates brittle failure. The specimens $S_{97.5}C_0Rc_{2.5}$and$S_{95}C_0Rc_5$ show a single dominant inclined shear plane at failure (Fig. 4.12(b) and 4.12(c)), which is similar to clayey soil and may be responsible for the almost identical post-peak behaviour as shown in Fig. 4.5. In contrast, the specimens $S_{92.5}C_0Rc_{7.5}$develop multiple cracks and specimens $S_{90}C_0Rc_{10}$ develop multiple cracks with bulging at the base as shown in Figs. 4.12(d) and 4.12(e). The formation of small fissures in the specimens $S_{92.5}C_0Rc_{7.5}$and $S_{90}C_0Rc_{10}$result into redistribution of stresses inside the specimen. As can be observed from Fig. 4.5 that the specimen with 7.5% and 10% rubber crumbles fails at higher deformation and show the inducement of ductility.

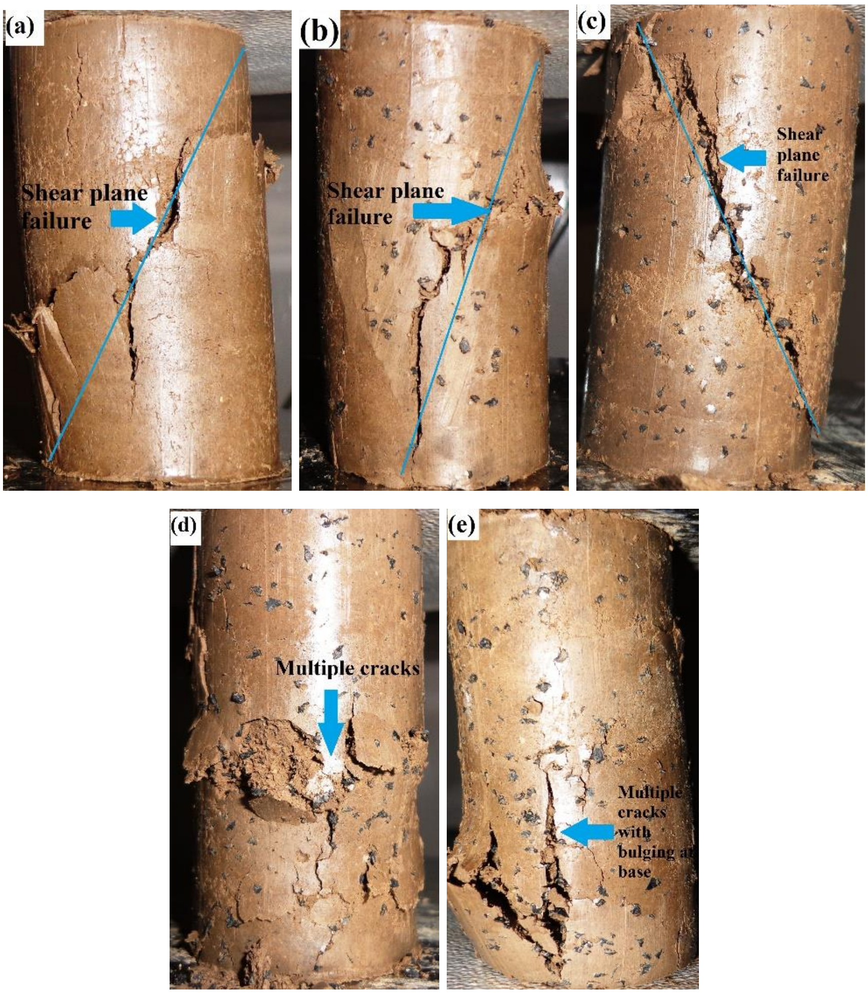


Fig. 4.12 Typical failure patterns under unconfined compressive strength test**: (a)** $S_{100}C_0Rc_0$, **(b)** $S_{97.5}C_0Rc_{2.5}$, **(c)** $S_{95}C_0Rc_5$, **(d)** $S_{92.5}C_0Rc_{7.5}$, **(e)** $S_{90}C_0Rc_{10}$

The cracking pattern of clayey soil specimens containing 2.5%, 5%, 7.5%, and 10% rubber fibres are shown in Figs. 4.13(a) to 4.13(e). The inclined shear plane failure has been observed in clayey soil specimens containing 2.5% and 5% rubber fibre content (Fig. 4.13(b)-(c)), which may be responsible for almost identical post-peak behaviour of the specimens as shown in Fig. 4.6. In contrast, the specimens $S_{92.5}C_0Rf_{7.5}$ and $S_{90}C_0Rf_{10}$predominantly exhibit bulging failure with micro cracks formation (Fig. 4.13(d)-(e)), which may be responsible for the increment in axial deformation and inducement of ductility as shown in axial load-deformation curves in Fig. 4.6. The formation of multiple cracks in clay-rubber crumbles and clay-rubber fibres specimens may be due to (i) evolution of tensile stress on the surface of rubber particle; (ii) soft aggregate like behaviour of rubber in the specimens.

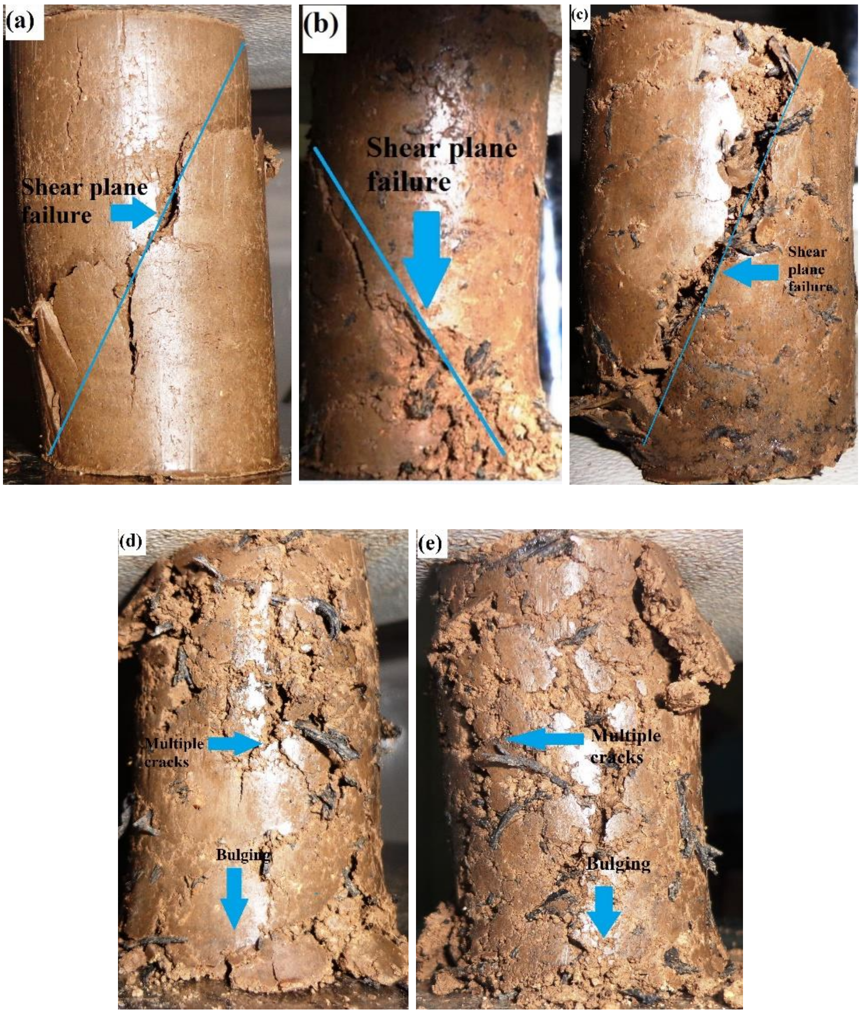


Fig. 4.13 Typical failure patterns under unconfined compressive strength test**: (a)** $S_{100}C_0Rf_0$, **(b)** $S_{97.5}C_0Rf_{2.5}$, **(c)** $S_{95}C_0Rf_5$, **(d)** $S_{92.5}C_0Rf_{7.5}$, **(e)** $S_{90}C_0Rf_{10}$

4.3.6 Unconfined Compressive Strength

The results of unconfined compressive strength (UCS) of the clayey soil containing rubber crumbles and rubber fibres are shown in Fig. 4.14. Fig. 4.14 reveals that the unconfined compressive strength of clayey soil increases marginally from 60.59 kPa to 61.87 kPa and 63.71 kPa with the inclusion of 2.5% and 5% rubber crumbles. Beyond 5% incorporation of rubber content, the unconfined compressive strength of clayey soil decreases. Srivastava et al. (2014)reported similar results in the stabilization of black cotton soil with waste rubber tires. The loss of friction and bonding between the clay and rubber crumble particles may have led to reduction of unconfined compressive strength(Kim and Kang 2011). The rate of reduction of unconfined compressive strength of clayey soil with inclusion of higher rubber crumbles content is high. The unconfined compressive strength of clay decreases by 8.89% and 25.06%, as the content of rubber crumbles increases from 7.5% to 10%, respectively. At higher rubber content, the behavior of the composite is governed by rubber crumbles particles to particles interaction rather than clay particles to rubber crumbles particles interaction may result in the higher rate of loss of strength.

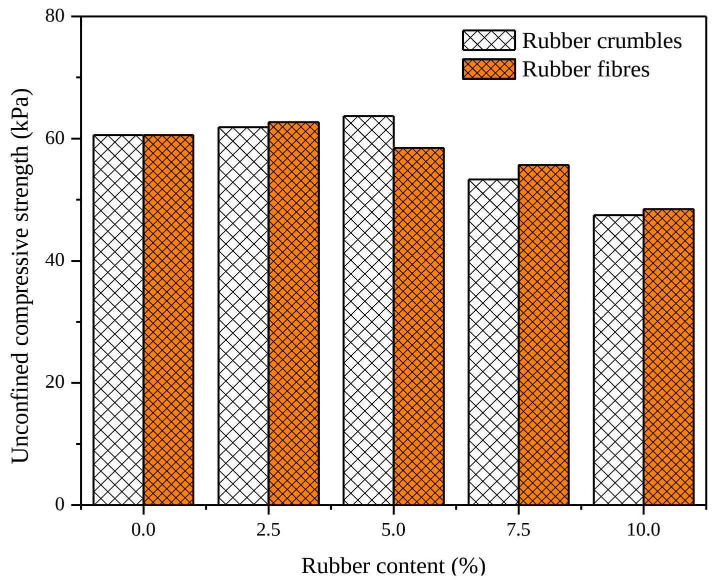


Fig. 4.14 Unconfined compressive strength of clayey soil mixed with rubber crumbles and rubber fibres

It can be inferred from Fig. 4.14 that the unconfined compressive strength of clayey soil specimen increases marginally from 60.59 kPa to 62.69 kPa with the addition of 2.5% rubber fibres content. Further incorporation of rubber fibres reduces the unconfined compressive strength of clay. For example, when rubber fibre content was increases from 7.5% to 10%, the unconfined compressive strength decreases by 12.30% and 21.71%, respectively as compared to the clayey soil. The reduction of unconfined compressive strength at 7.5% and 10% rubber fibres content may be due to increase in interaction between the rubber fibres and accumulation of rubber fibres. It may be noted that, earlier also, the maximum improvement in unconfined compressive strength of soil was reported by Akbulut et al. (2007)with the addition of 2% rubber fibres of 10 to 15 mm length. Whereas, Signes et al. (2016) experienced the reduction of 9.3%, 41.86%, 65.12%, 69.77%, and 81.34% with the addition of 2.5%, 5%, 10%, 15%, 20%, and 25% crumb rubber, respectively in clayey soil.

The specimens of clay-rubber crumbles and clay-rubber fibres disintegrated while soaking as shown in Fig. 4.15 and hence, the results of clay-rubber crumbles and clay-rubber fibres specimens have not been shown.

Fig. 4.15 Disintegration of clayey soil-rubber crumbles specimens after being immersed in water

4.4 TENSION BEHAVIOUR

4.4.1 Load-Diametral Deformation Response

The variation of tensile load - diametral deformation of clayey soil containing different content of rubber crumbles and rubber fibres are shown in Figs. 4.16 and 4.17. It is observed from Fig. 4.16 that the tensile load of clayey soil increases marginally with the increase in percentage of rubber crumbles up to 5%. For example, the peak tensile load of specimen S_{ref} was 0.0731 kN, which increased to 0.0781 kN and 0.0855 kN, for specimen $S_{97.5}C_0R_{2.5}$ and $S_{95}C_0R_5$, respectively. Further incorporation (i.e. 7.5% and 10%) of rubber crumbles reduces the split tensile strength of clayey soil.

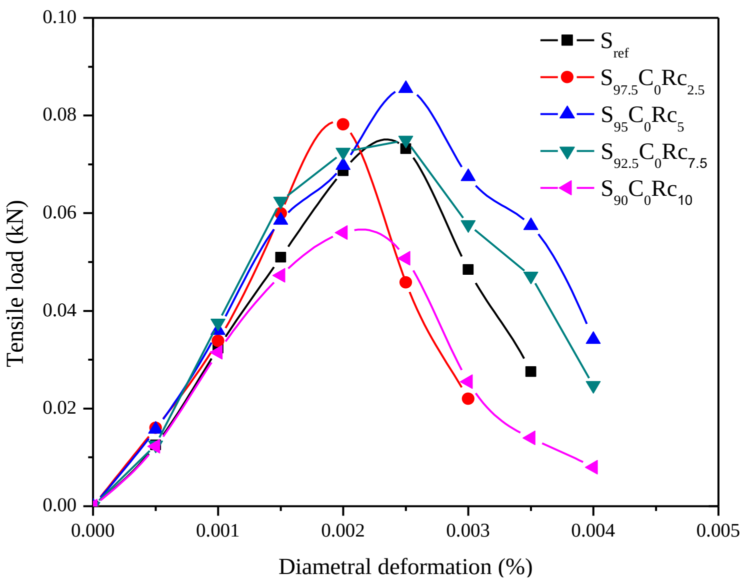


Fig. 4.16 Tensile load- diametral deformation of clayey soil mixed with rubber crumbles

The tensile load -diametral deformation behaviour of clayey soil mixed with 2.5%, 5%, 7.5% and 10% rubber fibres are shown in Fig. 4.17. It can be seen from Fig. 4.17 that tensile load of the mixtures increases prosaically with increasing the diametral deformation until a maximum tensile load value is reached. Fig. 4.17 reveals that the peak tensile load of clay containing 2.5% rubber fibres is higher than clayey soil. For example, the peak tensile stress of specimen $S_{100}C_0Rf_0$ was 0.0731 kN, which increased to 0.0816 kN for specimen $S_{97.5}C_0Rf_{2.5}$. Whereas, clayey soil containing 5% and 7.5% rubber fibres has almost similar peak tensile load as that of clay. A vigorous reduction in the peak split tensile stress of clay is seen from 0.0731 kN to 0.0539 kN when 10% rubber fibres were incorporated.

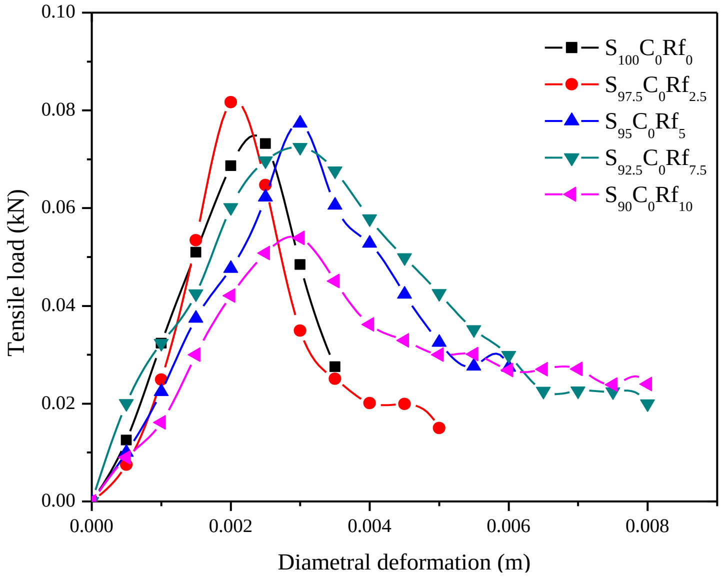


Fig. 4.17 Tensile load- diametral deformation of clayey soil mixed with rubber fibres

Fig. 4.16 reveals that the diametral deformation at failure of clayey soil increases with the inclusion of rubber crumbles up to 5%. For example, the diametral deformation of clayey soil- rubber crumbles specimen was increased from 0.002 m to 0.0025 m as the content of rubber crumbles increased from 2.5% to 5%. Beyond that, no further improvement in the diametral deformation was observed with the increase in rubber crumbles content. Similarly, Fig. 4.17 shows that the specimens $S_{95}C_0Rf_5$, $S_{92.5}C_0Rf_{7.5}$, and $S_{90}C_0Rf_{10}$ have same the diametral deformation at failure of 0.003 m.

The initial stiffness of clayey soil specimens without and with rubber crumbles and fibres is almost remains unchanged as shown in Figs. 4.16 and 4.17. The reduction in post-peak behavior of clayey soil-rubber crumbles mixtures under tensile load is different as compared to the compressive load. It is observed from Fig. 4.17 that the rate of loss of post-peak tensile load of clayey soil- rubber crumbles specimens under tensile load is more as compared to loss under compressive load. It is an indication of inability of interfacial mechanical interaction between the rubber crumbles and clay particles to restrict the sliding of rubber particles under tensile loads. The post-peak behaviour of specimen $S_{100}C_0Rf_0$ and$S_{100}C_0Rf_{2.5}$ is nearly similar as shown in Fig. 4.17. The rate of post-peak tensile load reduction of specimen $S_{100}C_0Rf_0$ and$S_{100}C_0Rf_{2.5}$ is higher, which indicates the brittle nature of specimens. The inclusion of more than 2.5% rubber fibres content prolongs the deformation taking ability of the clay and shows strain-hardening behaviour. The reduction in post-peak tensile loads of clay-rubber fibres mixtures indicates the gradual transformation from brittleness to ductility. The reduction in rate of loss of post-peak tensile loads may be due to the bridge effect of rubber fibres, which prevents the propagation of cracks through specimens.

4.4.2 Absolute toughness in tension

The area under tensile load - diametral deformation curve up to failure as shown in the Fig. 4.18is termed as the absolute toughness or energy absorption of the mixture. The results of absolute toughness in tension of clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber crumbles and rubber fibres is shown in Fig.4.19.

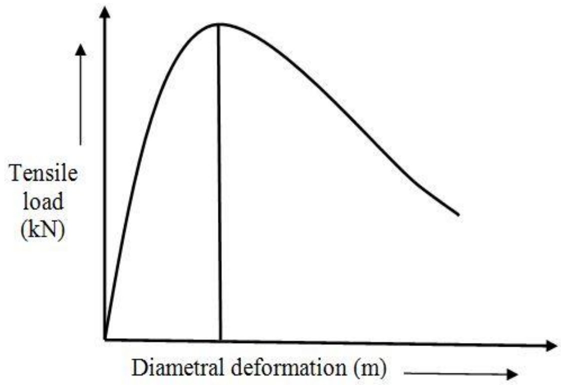


Fig. 4.18 Diagrammatic view of the tensile load-diametral deformation area used for calculation of absolute toughness

Study of Fig. 4.19 reveals an increase in the absolute toughness under tension of clayey soil with the inclusion of rubber crumbles up to 5%. For example, the absolute toughness under tension of specimen S_{ref} was 0.00010 kN.m, which increased to 0.000113 kN.m for specimen $S_{95}C_0Rc_5$. Similarly, an increase in the absolute toughness of clayey soil as evident from Fig. 4.17 was also observed with the inclusion of rubber fibres up to 7.5%. The inclusion of 7.5% rubber fibres increases the absolute of clayey soil from 0.00010 kN.m to 0.000134 kN.m. Further inclusion of rubber crumbles (>5%) and rubber fibres (>7.5%) reduces the absolute toughness of clayey soil. For example, the absolute toughness of specimens $S_{92.5}C_0Rc_{10}$ and $S_{92.5}C_0Rf_{10}$ was 0.000059 kN.m and 0.000087 kN.m, respectively.

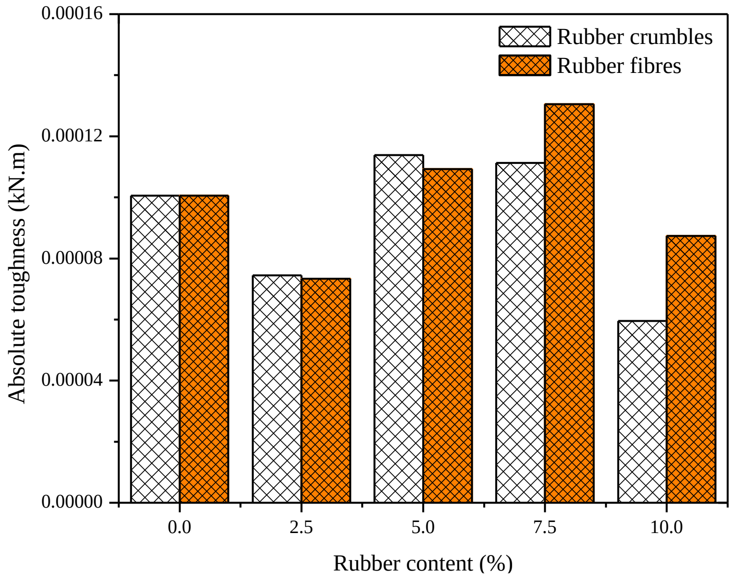


Fig. 4.19 Absolute toughness of clayey soil mixedwith rubber crumbles and rubber fibres in tension

4.4.3 Post peak Tensile Response

In order to find out the significance of rubber crumbles/fibres on toughening characteristics, especially in post peak tensile region, the load axis of tensile load - deformation diagram was normalized with respect to peak tensile load, and deformation axis was normalized with respect to deformation occurring at peak tensile load. Figs. 4.20 and 4.21show the variation of normalized tensile load with normalized deformation of clayey soil mixed with 0%, 2.5%, 5%, 7.5%, and 10% rubber crumbles and rubber fibres.

An examination of Fig. 4.20 reveals a sharp drop in the post peak tensile region of clayey soil specimen. The specimen $S_{97.5}C_0Rc_{2.5}$ also shows a sharp drop in post peak tensile region as shown in Fig. 4.20. Whereas, the specimen of clayey soil mixed with rubber crumbles (>2.5%) and rubber fibres were observed to follow a gradual decline after attaining the peak in normalized tensile load–diametral deformation curve. Thus from the above, it can be concluded that inclusion of rubber crumbles and rubber fibres in the clayey soil improves its post peak behavior in tension.

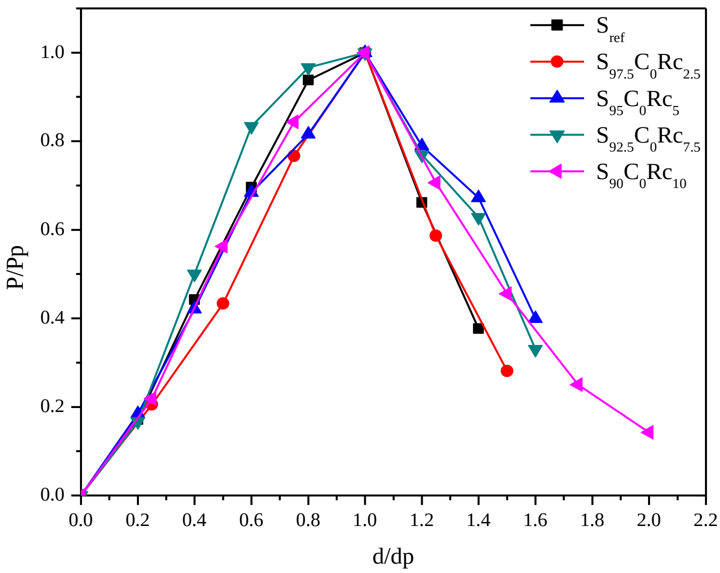


Fig. 4.20 Normalized tensile load - deformation of clayey soil mixedwith rubber crumbles

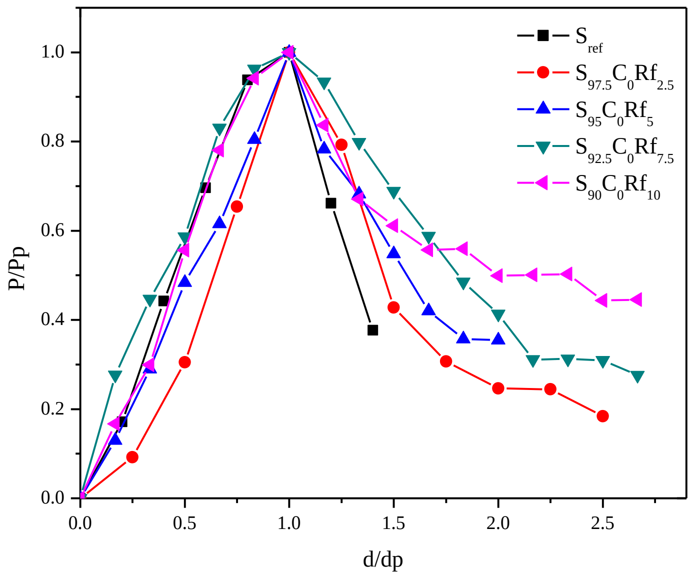


Fig. 4.21 Normalized tensile load - deformation of clayey soil mixedwith rubber fibres

4.4.4 Toughness Index in Tension

In order to specifically find out the significance of rubber crumbles and rubber fibres inclusion on the post peak tensile region of clayey soil and to compare their performance with an elastic–perfectly material, a dimensionless toughness index in tension (TI) as reported by Sobhan and Mashnad (2002) was calculated by using the following formula.

$$TI = \frac{Ad - Ap}{(d/dp - 1)} \tag{4.2}$$

Where

dp= deformation at peak tensile load Pp.

d= any deformation that is greater than dp value.

Ap= area under the normalized curve upto peak.

Ad= area under the normalized curve upto the deformation ratio d/dp.

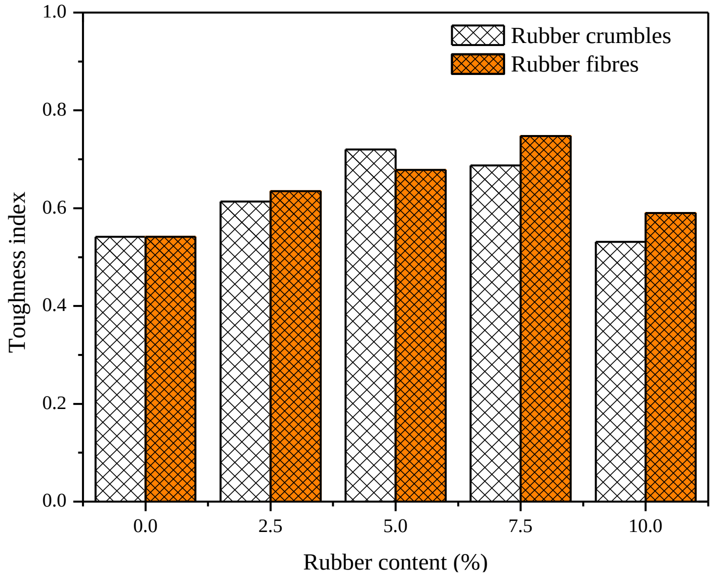


Fig. 4.22 Toughness index of clayey soil mixed with rubber crumbles and rubber fibres

For the elastic – perfectly material the value of TI is unity for any value of deformation ratio. On the other hand, TI is zero for an ideal brittle material. Fig. 4.22 shows the value of toughness index in tension of the clayey soil mixed with rubber crumbles and rubber fibres. Fig. 4.22 reveals that toughness index of clayey soil mixed rubber crumbles in tension increases with the inclusion of rubber crumbles up to 5%. For, example, for specimen S_{ref}, the toughness index was 0.541 which increased to 0.720 for specimen $S_{95}C_0Rc_5$. Similar trend of increase in toughness index as evident from Fig. 4.22 was observed with the inclusion of rubber fibres up to 7.5% in the clayey soil. For example, the toughness index under tension for the specimen S_{ref} was 0.541, which increased to 0.747 for specimen $S_{95}C_0Rf_{7.5}$. Addition of rubber crumbles and rubber fibres beyond 5% and 7.5% reduces the toughness index of clayey soil.

4.4.5 Cracking Pattern in Tension

The clayey soil specimen failure along the central vertical plane is shown in Fig. 4.23(a). Similarly, vertical cracking pattern was observed in the specimen $S_{97.5}C_0Rc_{2.5}$, $S_{95}C_0Rc_5$, and

$S_{92.5}C_0Rc_{7.5}$and such specimens were observed to split into two halves at the attainment of peak tensile load as shown in Figs. 4.23(b) to 4.23(d). The formation of multiple/ staggered cracks as shown in Fig. 4.23(d) in the specimen $S_{90}C_0Rc_{10}$may be responsible for the higher deformation after attainment of peak tensile load (as shown in Fig. 4.16).

Fig. 4.24(a) to 4.24(e) show the cracking pattern of specimens of clayey soil mixed with various percentages of rubber fibres. The specimen of clayey soil mixed with rubber fibres shows staggered cracking pattern as shown in Figs. 4.24(b) and 4.24(e). The confinement provided by rubber fibres to clayey soil as shown in Fig. 4.24(d) do not allow the specimens to split into two halves, which helps to bear tensile loads even after attainment of peak tensile load (as shown in Fig. 4.17).

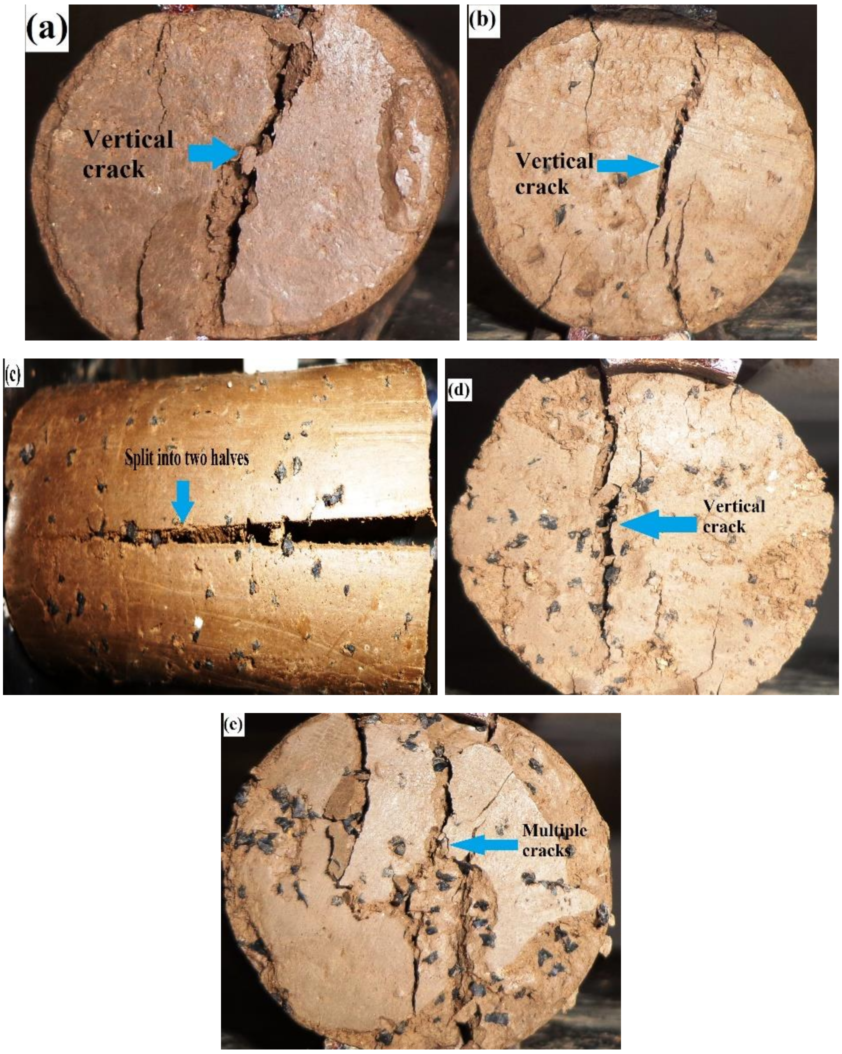


Fig. 4.23 Typical failure patterns under split tensile strength test: (a) $S_{100}C_0Rc_0$, (b) $S_{97.5}C_0Rc_{2.5}$, (c) $S_{95}C_0Rc_5$, (d) $S_{92.5}C_0Rc_{7.5}$, (e) $S_{90}C_0Rc_{10}$.

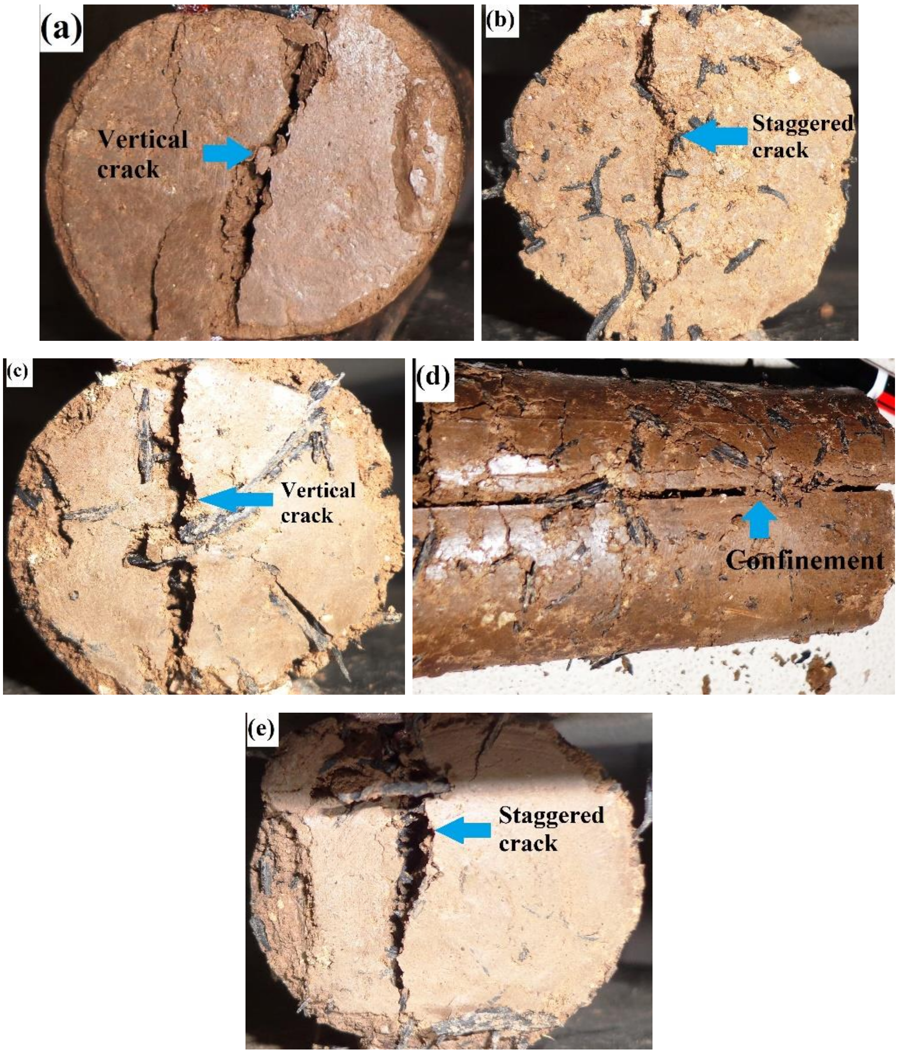


Fig. 4.24 Typical failure patterns under split tensile strength test: (a) $S_{100}C_0Rf_0$, (b) $S_{97.5}C_0Rf_{2.5}$, (c) $S_{95}C_0Rf_5$, (d) $S_{92.5}C_0Rf_{7.5}$, (e) $S_{90}C_0Rf_{10}$

4.4.6 Split Tensile Strength

It can be seen from the Fig. 4.25that tensile strength of the clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber crumbles and rubber fibres increases marginally with inclusion of rubber crumbles and rubber fibres up to 5% and 2.5%, respectively. For example, from Fig. 4.24 the tensile strength of specimen S_{ref} was 14.99 kPa, which increased to a value of 17.51 kPa and 16.98 kPa for specimen $S_{95}C_0Rc_5$ and $S_{97.5}C_0Rf_{2.5}$, respectively. Beyond 5% and 2.5% inclusion of rubber crumbles and rubber fibres, a decrement in the tensile strength was observed. At higher rubber content, the rate of loss of split tensile strength was more, which may be accredited to the (i) accumulation of rubber particles that leads to poor interaction between the clayey soil and rubber particles, (ii) difficulty in packing of lightweight rubber particles at higher content.

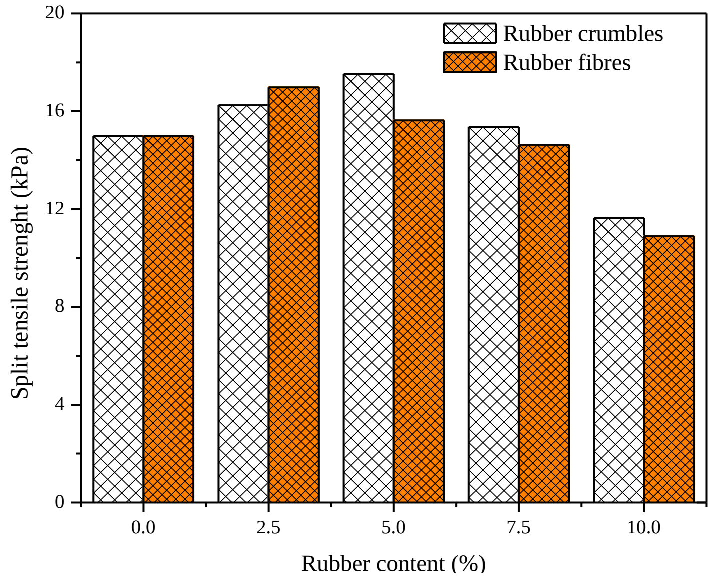


Fig. 4.25 Split tensile strength of clayey soil mixed with rubber crumbles and rubber fibres

4.5 CALIFORNIA BEARING RATIO VALUE

Load-penetration curve of clay-rubber crumbles mixtures obtained from California Bearing Ratio tests for both unsoaked and soaked condition are shown in Figs. 4.26 and 4.27.

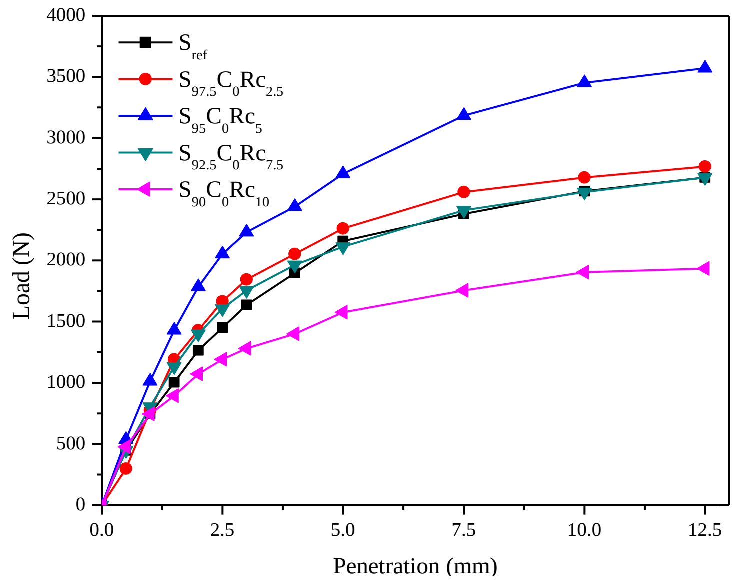


Fig. 4.26 Load- penetration curves of clayey soil-rubber crumbles mixtures (Unsoaked condition)

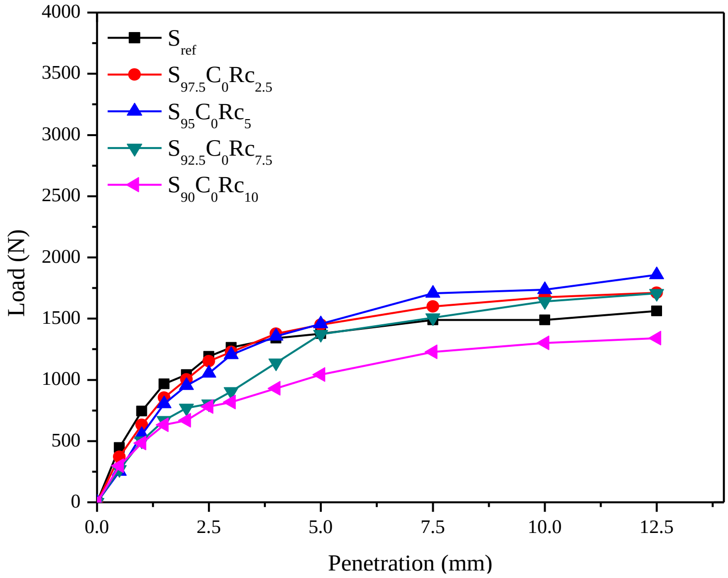


Fig. 4.27 Load- penetration curves of clayey soil-rubber crumbles mixtures (Soaked condition)

Fig. 4.28demonstrates that the California Bearing Ratio of clay was 10.59% and 8.69% in unsoaked and soaked conditions. Up to 5% inclusion of rubber crumbles, California Bearing Ratio of the clay in unsoaked condition increases, beyond that the trend reverses. The California Bearing Ratio values of clay containing 2.5% and 5% rubber crumbles in unsoaked condition was 12.16% and 14.99%, which reduced to 11.73% and 8.69%, as the content of rubber crumbles increased to 7.5% and 10%, respectively. These results were concord with Tajdini et al. (2016). At higher rubber content (i.e. 7.5% and 10%), the California Bearing Ratio value of clay decreases which may be attributed to the increase in contact points between rubber crumbles particles and high resilience of rubber particles which leads to the decrement of strength. The California Bearing Ratio values of clay in soaked condition decreases as the content of rubber crumbles increases. It is lower than the California Bearing Ratio value of mixtures in unsoaked conditions.

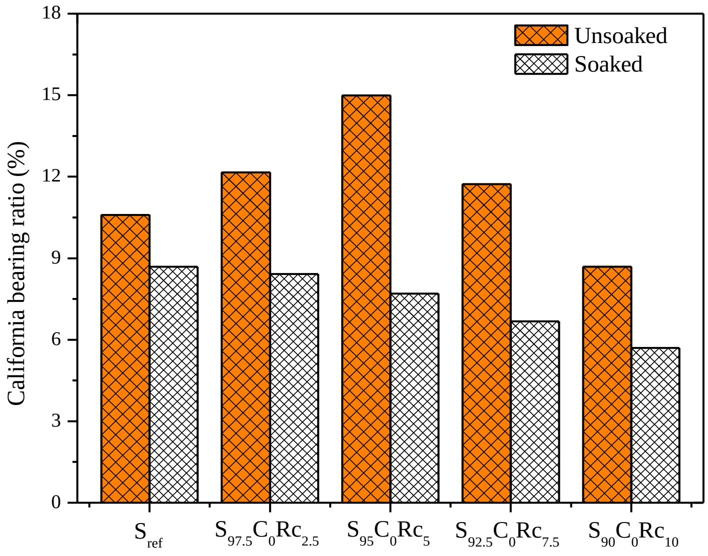


Fig. 4.28 Variation of California Bearing Ratio (%)of clayey soil mixed with rubber crumbles

Load-penetration curve of clay-rubber fibres mixtures obtained from California Bearing Ratio tests for both unsoaked and soaked condition are shown in Figs. 4.29 and 4.30.

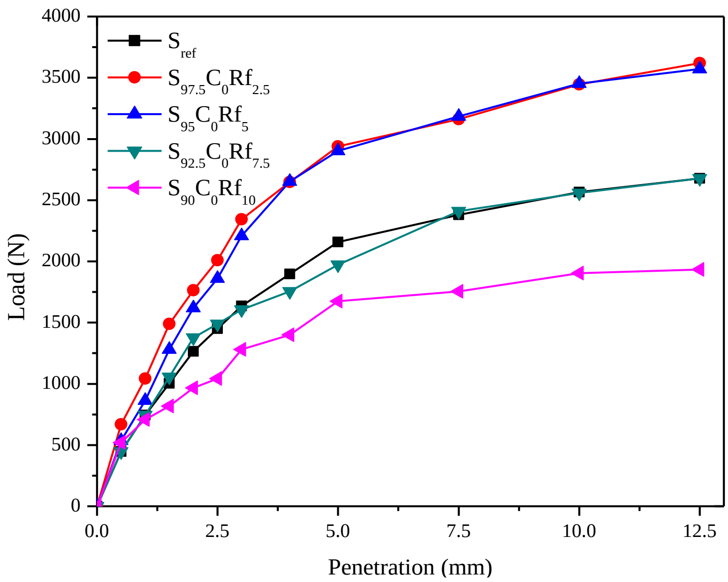


Fig. 4.29 Load- penetration curves of clayey soil-rubber fibres mixtures (Unsoaked condition)

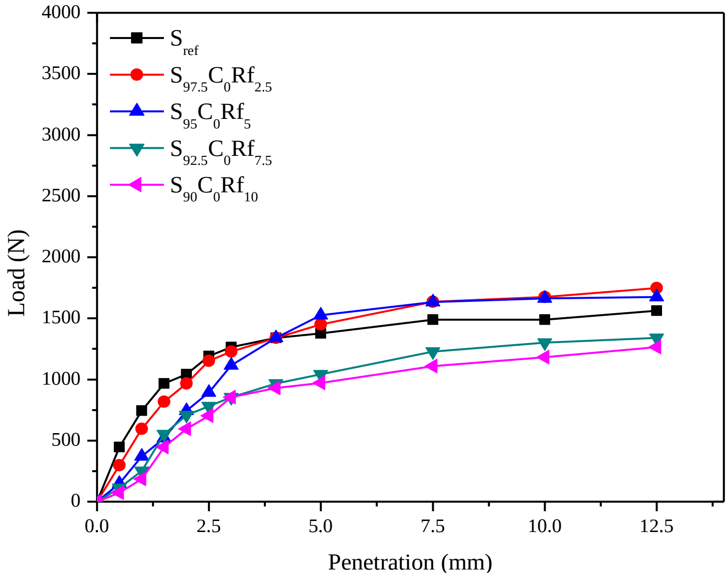


Fig. 4.30 Load- penetration curves of clayey soil-rubber fibres mixtures (Soaked condition)

The variation of California Bearing Ratio of clay-rubber fibres mixtures under the unsoaked and soaked conditions is presented in Fig. 4.31. It can be seen from Fig. 4.31 that the unsoaked California Bearing Ratio value of clay increases with the increase in rubber fibre content up to 2.5%. The improvement in unsoaked California Bearing Ratio value of clay was 38.56% with the addition of 2.5% rubber fibres. The inclusion of 7.5% and 10% rubber fibres substantially reduces the California Bearing Ratio value of clayey soil. The California Bearing Ratio value of clay decreases by 3.68%, 25.92%, and 44.44% with the increase in rubber fibres content from 2.5% to 5%, 7.5% and 10%, respectively. Sudden decrease in the CBR value of clay at higher rubber fibre content (> 5%) may be due to increase in interaction between the rubber fibres and accumulation of rubber fibres at higher content.

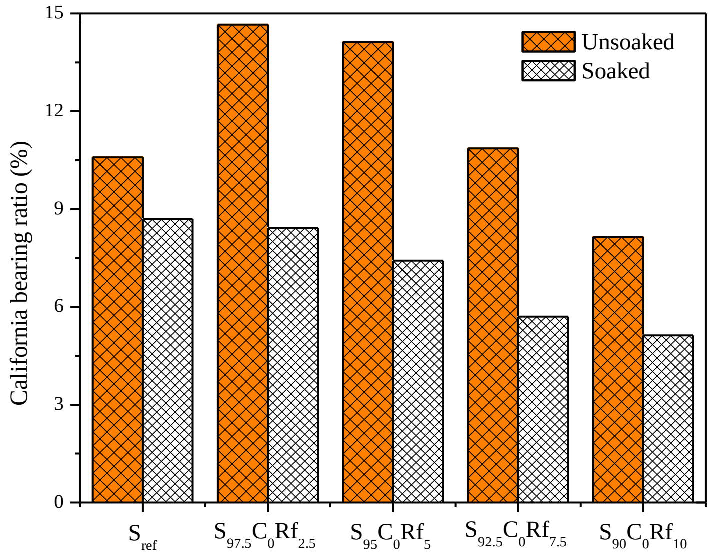


Fig. 4.31 Variation of California bearing ratio (%)of clayey soil mixed with rubber fibres

4.6 ONE-DIMENSIONAL CONSOLIDATION

Figs. 4.32 and 4.33 represent the vertical strain –log σ' plots of clayey soil mixed with rubber crumbles and rubber fibres. The gradient of consolidation curve line changes due to the inclusion of rubber crumbles/fibres. A steep post yield gradients are observed for clayey soil having no rubber, followed by 2.5%, 5%, 7.5% and 10% rubber content. It is perhaps due to semi-granular sandy material like behaviour of rubber, which acts as a flexible cushion to reduce the settlement and improves the stiffness. A small amount of rubber content (< 5%) does not contribute much to the stiffness improvement of soil.

The non linear vertical strain vs. log (pressure) response of the composite was observed. These results were in agreement with the results reported by Ho et al. (2010). Ho et al. (2010) reported that the quantity of rubber chips controls the stiffness of clay. The inclusion of cement reduced the compressibility of clay and increased the yield stress of mixtures. The high amount of tire chips turned the mixtures into granular material and gave more sufficient stiffness than cementation which was attributed as reasons for such observations. The possible reason for non-linearity of the curve may be that the composite was non homogenous and isotropic. Apart from that the compressibility of the rubber and clayey soil was also not equal. (Promputthangkoon and Kanchanachetanee, 2013).

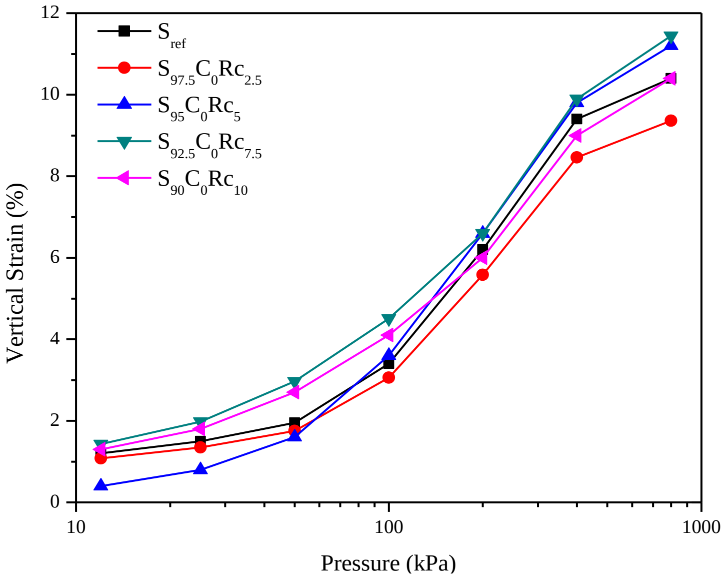


Fig. 4.32 Compression Curves of clayey soil mixed with rubber crumbles

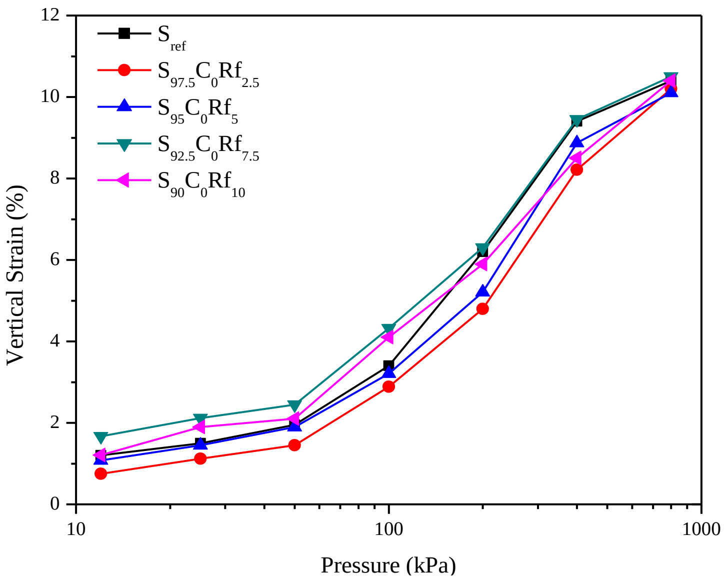


Fig. 4.33 Compression Curves of clayey soil mixed with rubber fibres

The variation of compression index (C_c) of clayey soil mixed with rubber crumbles and rubber fibres is shown in Fig. 4.34. The compression index of clay increases as the content of rubber crumbles increases. The inclusion of 2.5% to 10% rubber crumbles increases the C_c of clayey soil from 0.4625 to 0.468 and 0.527, respectively. Similarly, the compression index of clayey soil increases as content of rubber fibres increases in the clayey soil. For example, for specimen S_{ref}, the compression index was 0.4625, which increased to 0.463, 0.469, 0.489, and 0.510 for specimen $S_{92.5}C_0Rf_{2.5}$, $S_{95}C_0Rf_5$, $S_{92.5}C_0Rf_{7.5}$, and $S_{90}C_0Rf_{10}$, respectively. The increase in compression index of clayey soil with the incorporation of rubber particles may be attributed to incompressibility of the rubber crumbles/fibres. The unequal compressibility of rubber and clayey soil particles increases the void ratio of the composite.

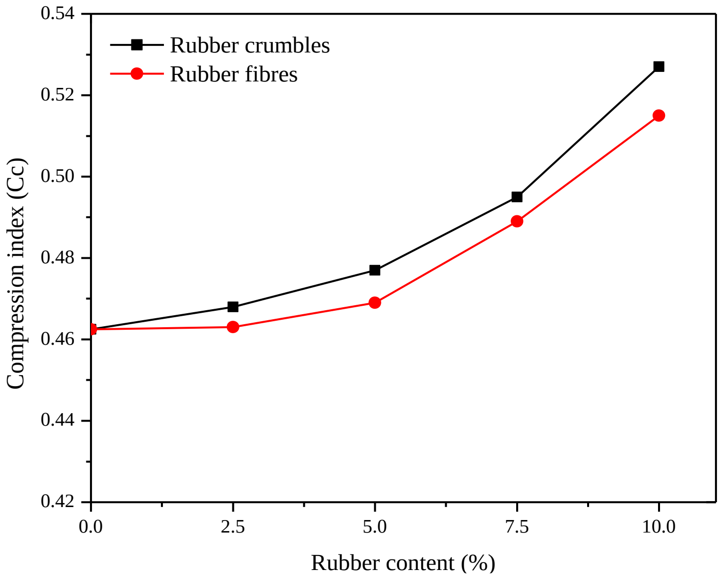


Fig. 4.34 Variation of compression index (C_c) of clayey soil with rubber crumbles and rubber fibres content

These results are found contrary to results reported by other investigators(Ho et al. 2010; Mukherjee and Mishra 2017). Mukherjee and Mishra (2017) had shown in their investigation on bentonite- sand mixture containing tyre chips as a liner material that C_c of the mixture reduces marginally with the inclusion tyre chips up to 10%. The reduction in C_c of mixture was credited to the reduction of void ratio with the inclusion of tyre chips. Further inclusion of tyre chips reverses the trend of C_c was attributed to compression of tyre-to-tyre interaction. Srivastava et al. (2014) also carried out consolidation study of expansive soil containing 10% to 30% shredded tyre and reported that inclusion of shredded tyre increases the C_c of the soil.

4.7 SWELLING PRESSURE

The effect of inclusion of rubber crumbles and rubber fibres on swelling pressure of clayey soil evaluated by the laboratory investigation is shown in Fig. 4.35. It is observed from Fig. 4.35 that addition of rubber crumbles reduces the swelling pressure of clay. The swelling pressure value of clayey soil decreases from 70.12 kPa to 66.45 kPa, 58.33 kPa, 51.66 kPa, and 45.78 kPa, with the inclusion of 2.5%, 5%, 7.5%, and 10% rubber crumbles, respectively. Similarly, incorporation of rubber fibres in clayey soil reduces the swelling pressure too as shown in Fig. 4.35. The inclusion of 2.5%, 5%, 7.5%, and 10% rubber fibre content reduces the swelling pressure of clayey soil by 11.32%, 24.72%, 33.59%, and 43.53%, respectively.

The possible reason of this reduction in swelling pressure of clayey soil with incorporation of rubber crumbles/fibres is the creation of drainage paths for dissipation of pore pressures and replacement of swelling clay particles by non-swelling rubber particles and confinement effect, which is able to encounter tensile stress induced due to the swelling of clayey particles. Signes et al. (2016) also reported the reduction in free swelling of clayey soil with the inclusion of rubber particles.

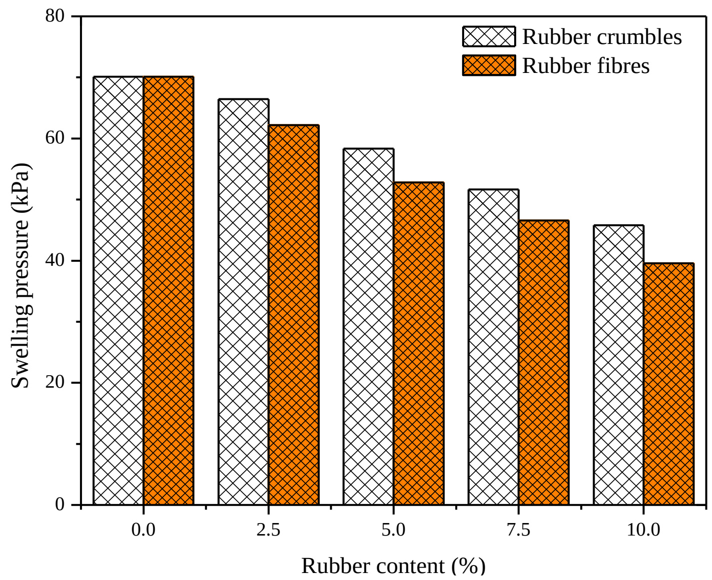


Fig. 4.35 Variation of swelling pressure of clayey soil mixed with rubber crumbles and rubber fibres

4.8 DURABILITY BEHAVIOUR

The specimens of clay-rubber crumbles and clay-rubber fibres were unable to resist the first cycle of wet-dry process and disintegrated completely as shown in Fig. 4.36 because of intrusion water through the cavities.

Fig. 4.36 Disintegrated specimens of clay-rubber crumbles during first cycle of durability test

4.9 MORPHOLOGICAL STUDIES

SEM images of clayey soil containing 0% and 5% rubber crumbles specimens are shown in Figs. 4.37(a) and 4.37(b). The dark portions of SEM images are assumed to be voids in the specimens. A number of micro-cavities are observed in the clay specimen as shown in Fig. 4.37(a). Cracks and irregular shape of the rubber crumbles particles can be seen in Fig. 4.37 (b). The irregular shape may be helpful in entrapping the air during formation of specimen for the tests. The voids in specimen of clayey soil – rubber crumble can be seen in Fig. 4.37(b). At the interface of rubber crumble and clay particles gaps are observed (Fig. 4.37(b)) reflecting a weak bond between rubber crumble and clay particles. Similarly, a gap at interface of rubber fibre and clayey soil can be seen in Fig. 4.37(c). The cavity and micro cracks on the surface of rubber fibres as shown in Fig. 3.7(b) (Section 3.2.4), may responsible for the poor adhesion between the clayey soil and rubber fibres, which may lead to gap creation at interface. The trend of reduction in unconfined compressive strength and split tensile strength observed in Section 4.3 and 4.4 respectively may be attributed to the weak interfacial bond between rubber and clay particles. These gaps may also be responsible for the reduction in soaked California Bearing Ratio values and swelling pressure of clay-rubber crumbles/fibres mixtures as were observed in Section 4.5 and 4.7, respectively.

These observations were in agreement with the result reported by the other investigator in the past (Segre and Joekes, 2000; Emiroğlu et al., 2007; Reda Taha et al., 2008; Wang and Mei, 2012; Gupta et al., 2014, 2015a, 2015b, 2016, 2017; Hannawi et al., 2016) on the concrete containing waste rubber tire as partial replacement of cement, fine and coarse aggregate. The soil water retention characteristics and matrix suction of the proposed composite was no evaluated in this investigation.

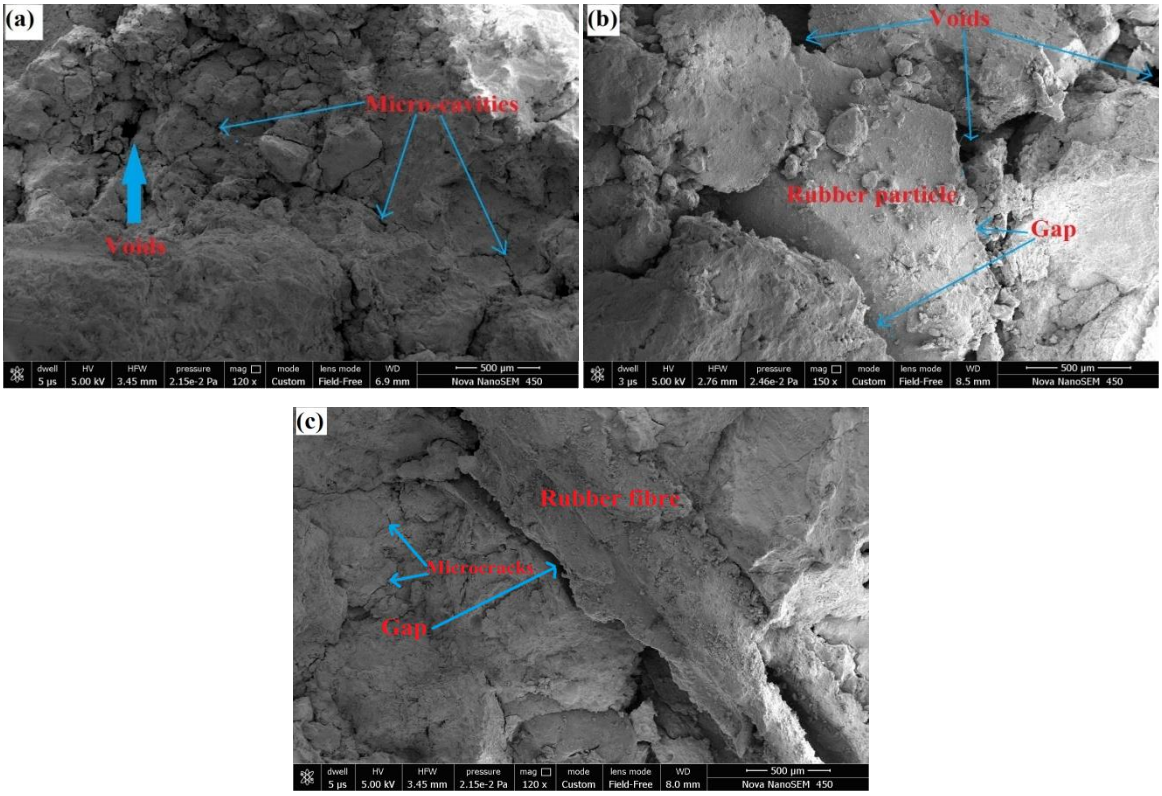


Fig. 4.37SEM Photograph of specimens **(a)** S_{ref} (5.00 KV, 120x, 500 µm), **(b)** $S_{95}C_0Rc_5$ (15.00 KV, 150x, 500 µm), **(c)** $S_{97.5}C_0Rf_{2.5}$ (5.00 KV, 120x, 500 µm).

4.10 CONCLUSIONS

4.10.1 Compaction studies

Maximum dry unit weight and optimum moisture content of the clayey soil decreases as the content of rubber crumbles and rubber fibres in the mixture increases.

4.10.2 Compression and Tension Behaviour

From the unconfined compression and tension behavior, the following may be generally concluded.

- Both unconfined compressive strength and split tensile strength of the clayey soil increases marginally with inclusion of rubber crumbles and rubber fibres up to 5% and 2.5%, respectively. The incorporation of higher amount of rubber crumbles and rubber fibres reduces the unconfined compressive strength and split tensile strength.

- The absolute toughness and toughness index in compression and tension of the clayey soil increases with inclusion of rubber crumbles and fibres up to 5% and 7.5%, respectively. The incorporation of rubber crumbles and rubber fibres above the 5% and 7.5% reduces the absolute toughness and toughness index in both compression and tension of the clayey soil.
- The axial deformation at failure of clayey soil- rubber crumbles and clayey soil-rubber fibres specimens under compression increases with the increase in rubber content. No increase in the axial deformation corresponding to the peak axial load was observed beyond 5% inclusion of rubber crumbles and rubber fibres in the case of specimens under tensile load.
- The inclusion of rubber crumbles and rubber fibres in clayey soil improves its post peak behavior in compression and tension by lowering the rate of loss of post-peak strength and improves strain-hardening characteristics.

➢ Inclusion of rubber crumbles and rubber fibres in the clayey soil changed the cracking pattern of specimen under compression from shear failure to multiple cracks. Similarly, Inclusion of rubber crumbles and rubber fibres in the clayey soil changed the cracking pattern of specimen under tension from catastrophic failure with vertical crack to multiple cracks.

➢ The complete disintegration of clayey soil, clayey soil-rubber crumbles and clayey soil-rubber fibres specimens was observed within few minutes after immersion in water.

4.10.3 California Bearing Ratio value

On increasing, the percentage of rubber crumbles and rubber fibres up to 5% and 2.5%, respectively the unsoaked California bearing ratio value of the clay increases. Further incorporation of rubber crumbles and rubber fibres reduces it. The continuous reduction in soaked California bearing ratio value of the clayey soil was observed with the inclusion of rubber crumbles and rubber fibres.

4.10.4 One-dimensional consolidation

The compression index of clayey soil increases with the increase in content of rubber crumbles and rubber fibres.

4.10.5 Swelling pressure

The swelling pressure of the clayey soil decreases with the increase in rubber crumbles and rubber fibres content.

4.10.6 Durability Behaviour

The specimen of clayey soil, clayey soil- rubber crumbles and clayey soil- rubber fibres mixtures disintegrate completely within few minutes of first wetting cycle of the test.

4.10.7 Morphological studies

Micro-structural analysis shows the weak interfacial bonding between the rubber crumbles/fibres and clayey soil and cracking occurred at the interface, which lead to reduction in strength.

CHAPTER 5

ASSESSMENT OF GEOTECHNICAL PROPERTIES OF CEMENTED CLAYEY SOIL INCORPORATED WITH WASTE RUBBER CRUMBLES

5.1 GENERAL

This chapter presents the results of compaction, unconfined compressive strength, split tensile strength, California Bearing Ratio, one-dimensional consolidation, swelling pressure, and durability tests conducted on the different combinations of clayey soil-cement-rubber crumbles mixtures along with the mineralogical and morphological studies to get better intuition about behavior of the composite. The effect of rubber crumbles content on the unconfined compression behavior and split tensile behavior of cement stabilized clayey soil were also discussed in this chapter. It may be recalled that the rubber crumbles and cement with content varying from 0 to 10% and 3% to 6% respectively, were mixed in the clayey soil.

5.2 COMPACTION STUDIES

The maximum dry unit weight and optimum moisture content of clayey soil-cement-rubber crumbles were determined by modified proctor tests. The compaction curves of different clayey soil-rubber crumbles mixtures containing 3% and 6% cement are shown in Figs. 5.1 and 5.2, respectively. The maximum dry unit weight of clayey soil (S_{ref}) was 16.3 kN/m^3 and optimum moisture content (post-compaction water content) was 20.9% (Fig. 4.1).

The variation of maximum dry unit weight and optimum moisture content of clayey soil-rubber crumbles mixtures containing 3% and 6% cement are shown in Figs. 5.3 and 5.4, respectively. It is observed from Fig. 5.3 and Fig. 5.4 that the maximum dry unit weight of clayey soil- cement mixtures decreases as the cement content increases. The maximum dry unit weight of S_{ref} was 16.3 kN/m^3, which reduced to 16.2 kN/m^3, and 16.1 kN/m^3 for mix $S_{97}C_3Rc_0$ and $S_{94.0}C_6R_0$, respectively. The optimum moisture content of clayey soil increases with the increase in cement content. The water content of S_{ref} was 20.9%, which increased to 21.3% and 21.9% for the mix $S_{97}C_3Rc_0$ and $S_{94}C_6Rc_0$, respectively. The cement reacts rapidly with the clay, causing changes in Base Exchange Aggregation (BEA) and the flocculation phenomenon. The void ratio of the mixtures increases due to the flocculation process. The increase in void ratio causes the decrease in dry unit weight of the mixtures. The increase in optimum moisture content may be attributed to the absorption of water, development of heat of hydration and additional water held within the flocs resulting from flocculation.

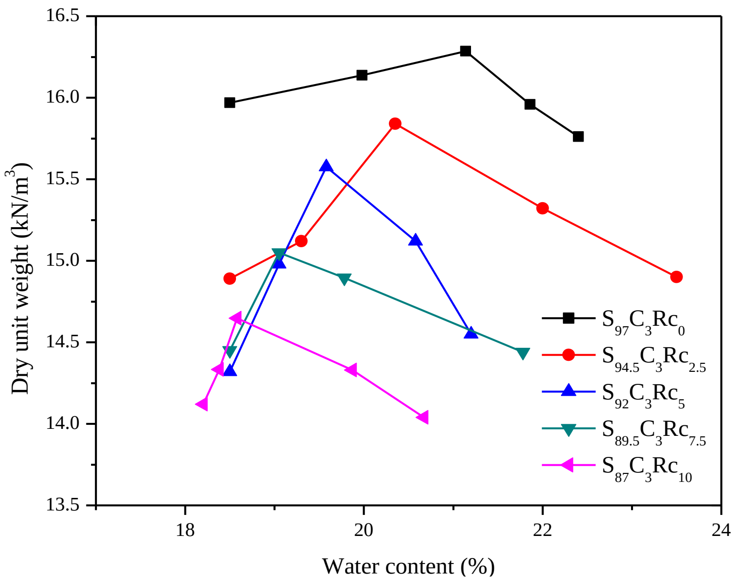


Fig. 5.1 Compaction curves of the clayey soil mixed with 3% cement and rubber crumbles

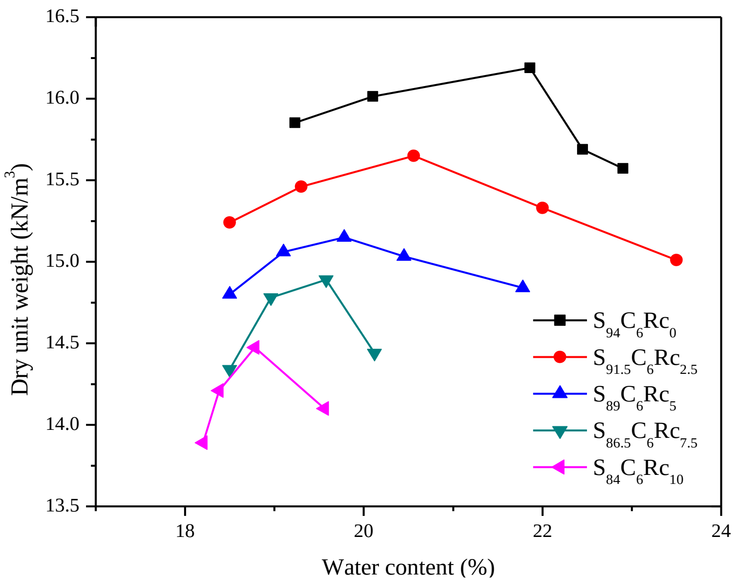


Fig. 5.2 Compaction curves of the clayey soil mixed with 6% cement and rubber crumbles

The combined effect of rubber crumbles and cement on maximum dry unit weight and optimum moisture content of the clayey soil are illustrated in Figs. 5.3 and 5.4. The introduction of rubber crumbles in cement stabilized clayey soil leads to reduction of maximum dry unit weight and optimum moisture content of the mixes. For example, the maximum dry unit weight of mix $S_{92}C_3Rc_5$was 15.6 kN/m^3, which decreased to 15.1 kN/m^3 for mix $S_{89}C_6Rc_5$.A reduction of 10.2% and 11.6% in the maximum dry unit weight is observed with the inclusion of 10% rubber in clayey soil stabilized with 3% and 6% cement content as compared to clay alone. The optimum moisture content of the composite decreases with the increase in rubber crumbles content, although it increases with increasing cement content of the mixture. Decrease in compaction parameters may be due to the loss of compaction efficiency (elastic response of rubber during compaction), low specific gravity and low water absorption capacity of rubber crumbles. The decrease in dry unit weight and optimum moisture content of clayey soil-cement-rubber crumbles mixtures with the increase in rubber crumbles content was in agreement with Cabalar et al. (2014) and Signes et al. (2016). However, these observations are in disagreement with earlier findings by Tiwari et al. (2017) and Priyadarshee et al. (2015), where an increase in dry unit weight and optimum moisture content was observed with the addition of waste rubber tires.

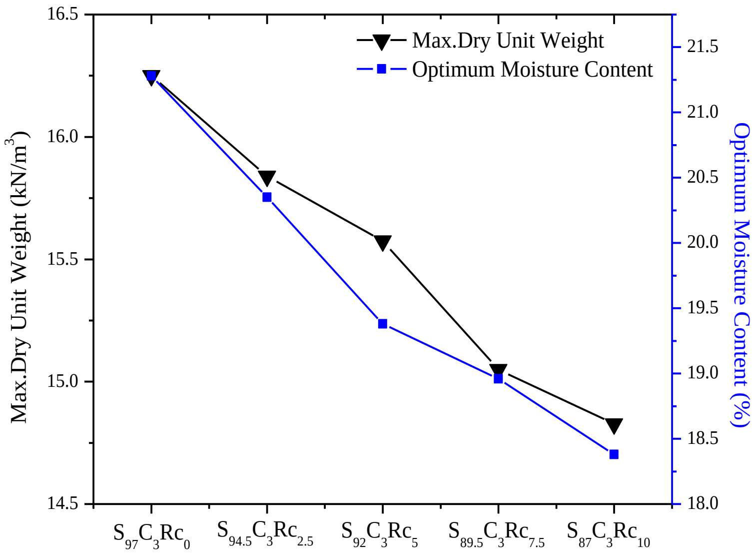


Fig.5.3 Variation of maximum dry unit weight and optimum moisture content of clayey soil-rubber crumbles mixtures containing 3% cement

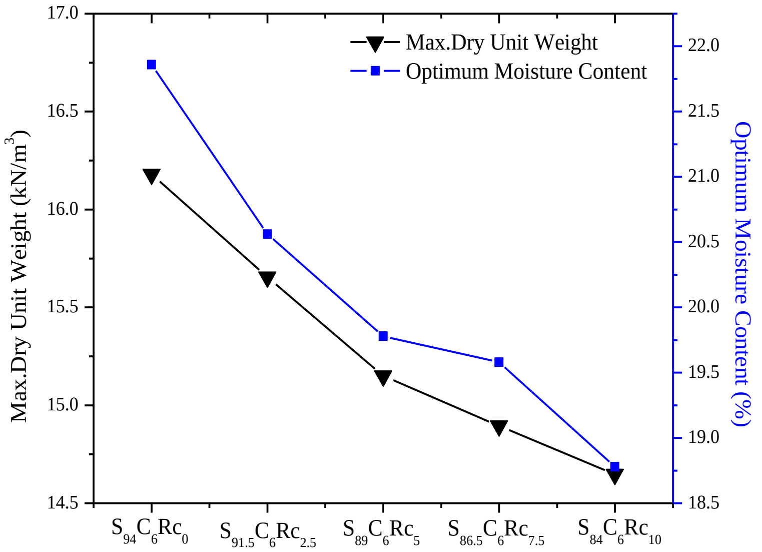


Fig.5.4 Variation of maximum dry unit weight and optimum moisture content of clayey soil-rubber crumbles mixtures containing 6% cement

5.3 UNCONFINED COMPRESSION BEHAVIOUR

5.3.1 Axial Load-Deformation response

The axial load-deformation response of clayey soil incorporated with 2.5%, 5%, 7.5%, and 10% rubber crumbles and 3% and 6% cement and cured for 28 days are shown in Figs. 5.5 and 5.6 (unsoaked condition). The axial load-deformation curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured in humidity controlled room for 28 days followed by immersion in water for 24 hours are shown in Figs. 5.7 and 5.8 (soaked condition). The curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured for 7 and 14 days for both unsoaked and soaked condition are shown in Appendix (Figs. A1 to A8). The effect of inclusion of rubber crumbles on axial load-deformation behaviour of clayey soil has already been discussed in section 4.3.1 of chapter 4.

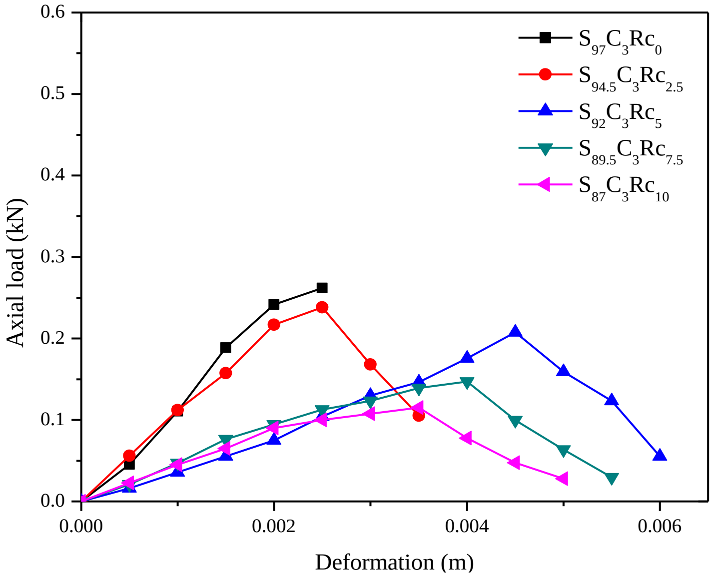


Fig. 5.5 Axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 28 days (Unsoaked condition)

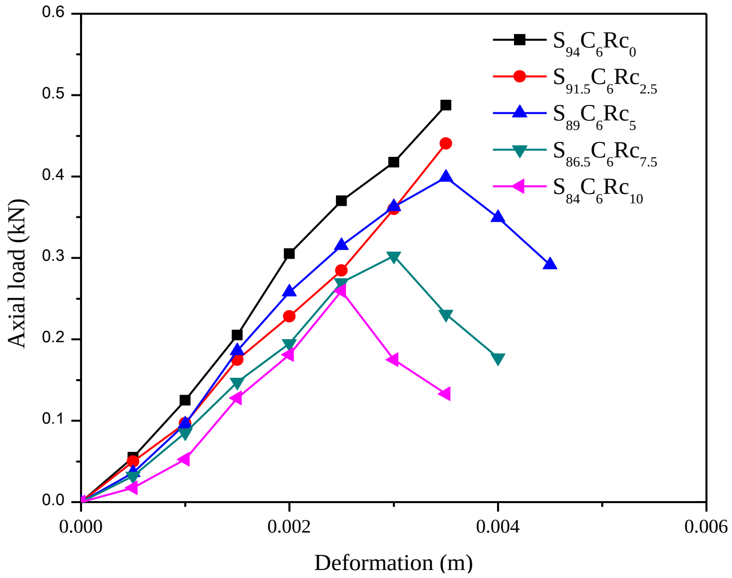


Fig. 5.6 Axial load- deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 28 days (Unsoaked condition)

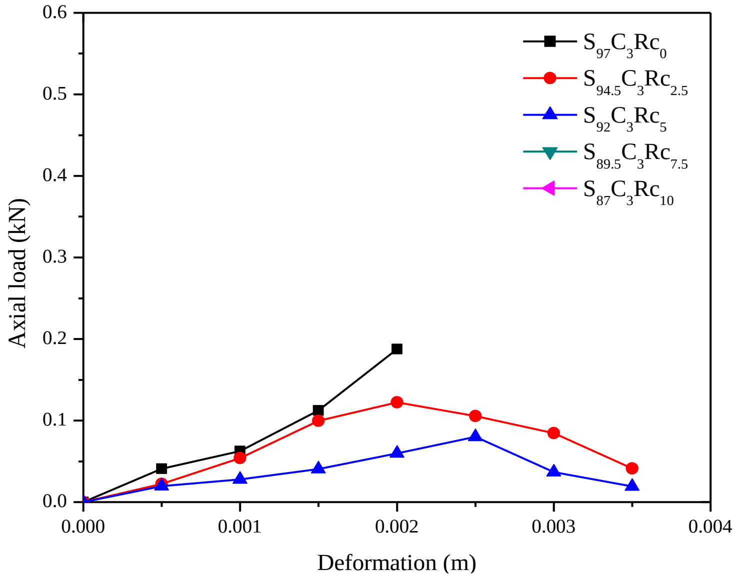


Fig. 5.7 Axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 28 days (Soaked condition)

The effect of inclusion of cement (3% and 6%) on axial load-deformation behaviour of clayey soil specimens cured for 28 days are shown in Figs. 5.5 and 5.6. It is observed that the axial load of clayey soil incorporated with cement increases with the increase in percentage of cement. For example, for specimen $S_{97}C_3Rc_0$, the peak axial load was 0.261 kN, which increased to 0.487 kN for specimen $S_{94}C_6Rc_{0.}$ Similar behaviour was also reported by Tang et al. (2007) in their investigation on cement stabilized clay reinforced with polypropylene fibre. Increase in axial load may be attributed to increase in relative per grain contact points of cement. Upon hardening, it affects a commensurate amount of bonding at the contact point. The inclusion of cement in clayey soil higher the stiffness and lower the failure strain, which is an indicative of brittle behaviour of the composite leaving no residual strength.

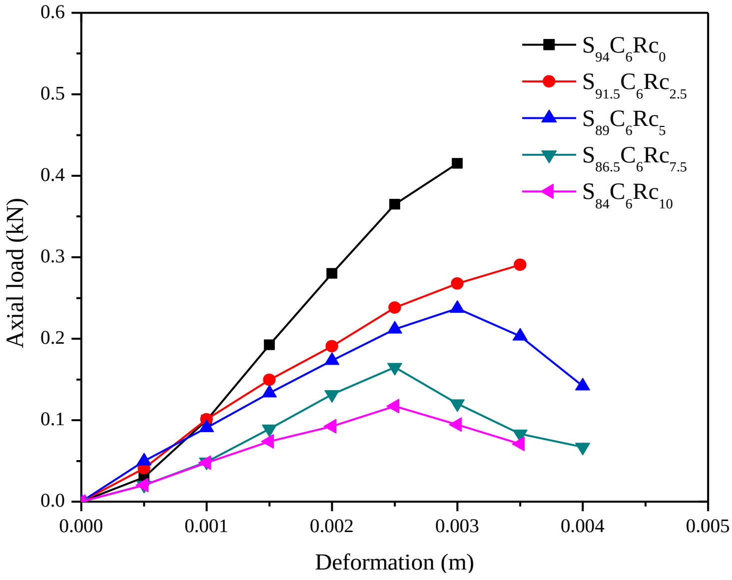


Fig. 5.8 Axial load- deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 28 days (Soaked condition)

While soaking, the 28 days cured specimens $S_{97}C_3Rc_0$ and $S_{94}C_6Rc_0$ do not disintegrate but there is a significant loss in the peak axial load as shown in Figs. 5.7 and 5.8. For example, for soaked specimens $S_{97}C_3Rc_0$ and $S_{94}C_6Rc_0$, the peak axial load was 0.187kN and 0.415kN, respectively, which is lesser than unsoaked specimens of the same proportion. The water intruded during soaking disrupts the inter particle contacts, and cement bonds are the possible reason for this conduct. Similar to the unsoaked specimens, the soaked specimens $S_{97}C_3Rc_0$ and $S_{94}C_6Rc_0$ exhibit much more brittle behaviour to that of untreated clayey.

The combined effect of cement and rubber crumbles on axial load-deformation behaviour of clayey soil cured for 28 days is delineated in Figs. 5.5 and 5.6 for unsoaked conditions. The peak axial load of clayey soil containing 3% and 6% cement decreases with the increase in percentage of rubber crumbles. For example, for 28 days cured specimen $S_{97}C_3Rc_0$, the peak axial load was 0.261 kN, which decreased to 0.204 kN, when 5% rubber crumbles were incorporated. Similarly, the peak axial load of specimens $S_{91.5}C_6Rc_{2.5}$ and $S_{89.0}C_6Rc_{5.0}$was 0.440 kN and 0.399 kN, which decreased to 0.302 kN and 0.259 kN for the specimens $S_{86.5}C_6Rc_{7.5}$ and $S_{84.0}C_6Rc_{10.0}$, respectively. Reduction in peak axial load may be attributed to the lesser stiffness of rubber crumbles as compared to the cemented clay and difficulties in the packing of lightweight rubber crumbles particles at high rubber crumbles content. The increase in percentage of rubber crumbles in clayey soil at the same cement content results in lower peak strength; higher failure deformation upto 5% inclusion of rubber crumbles and lowers the stiffness. The clayey soil-cement-rubber crumbles mixtures show some post failure resistance, which is due to the ability of rubber component to resist crack. Similar trend of decrease in peak axial load was observed for soaked specimens of clayey soil-cement-rubber crumbles mixtures with the increase in rubber crumbles content as shown in Figs. 5.7 and 5.8. From Figs. 5.7 and 5.8, it is depicted that due to immersion in water, the peak axial load of specimens decreases. For example, the peak axial load of specimen $S_{94}C_6Rc_0$was 0.487kN in unsoaked condition, which decreased to 0.412 kN after immersion. It is probably due to the development of low suction and dominancy of softening of the specimens over mechanism of amplification in the strength (pozzolanic reaction). The specimens $S_{89.5}C_3Rc_{7.5}$ and $S_{87}C_3Rc_{10}$ disintegrated as shown in Fig. 5.9, after being immersed in water indicating that treatment may be ineffective because the repulsive force of intruded water dominates over the attractive forces of cement bond.

Fig. 5.9 Disintegration of specimens after being immersed in water.

In Fig. 5.6, the specimen $S_{91.5}C_6Rc_{2.5}$ shows no post failure resistance because the ductility of rubber is offsetted by the brittleness of cementation. The specimens with rubber crumbles and cement (3%) exhibit more ductile behaviour and no distinct reduction in axial load is evident even at higher deformation. Gradual declines after procuring the peak axial loads are observed. It is perhaps due to the compressibility of the rubber particle and lesser formation of hydration product due to reaction between the clay and cement, which make the composite less stiff as compared to the composite stabilized with 6% cement. However, at 6% cement content, the brittleness of the composite could be overcome with the inclusion of rubber crumbles ≥ 5% in unsoaked conditions. At higher rubber content, the deformation corresponding to the peak load changes abruptly. This can be attributed to the (i) increase in the interaction between rubber to rubber particles; (ii) indigent interfacial mechanical interaction between rubber and cemented clay particles; (iii) decrease in friction and bonding between cemented clay and rubber particles (Kim and Kang, 2013); (iv) entrapping of air and soft particle like behaviour of rubber crumbles. Similar trend was observed for the soaked specimens as shown in Figs. 5.7 and 5.8. Wang and Song (2015) had also shown in their investigation that inclusion of crumb rubber in cemented clayey soil decreases the compressive strength and stiffness and improves the brittle behaviour of cemented clay to ductile. While, Took and Pedro (2014) reported an increase in the unconfined compressive strength with the incorporation of 5% rubber fibre of length 10 mm to 20 mm in cemented soils.

Figs. 5.5 to 5.8 reveal that the deformation at failure of cemented clayey soil increases with the inclusion of rubber crumbles. For example, for unsoaked specimen $S_{97}C_3Rc_0$, the deformation at failure was 0.0025 m, which increased to 0.0045 m for specimen $S_{92}C_3Rc_5$. A close examination of Figs. 5.5 to 5.8 shows an increase in deformation at failure with the increase in rubber crumbles content upto 5%, there after it reduces. For example, for unsoaked specimen $S_{97}C_3Rc_0$, the deformation at failure was 0.0025 m, which increased to 0.0045 m for specimen$S_{92}C_3Rc_5$and decreased to 0.004 m, and 0.0035 m for specimen$S_{89.5}C_3Rc_{7.5}$ and $S_{87}C_3Rc_{10}$, respectively. The inclusion of rubber crumbles helps in lowering the stiffness and introduces flexibility in the composite. This is contrary to test results of Ho and Chan (2010) on soft clay incorporated with rubber chips and cement, which stated that the axial strain of specimens increases with inclusion of rubber chips upto 10%. However, the difference in results may be due to the change in form of waste tires and properties of clay used in the investigation. Similar trend of increase in deformation at failure was observed for the soaked specimens up to 5% inclusion of rubber crumbles as evident in Figs. 5.7 and 5.8.

Examination of Fig. 5.5, Fig. 5.6and Appendix (Figs. A1 to A4) reveals that the peak axial load of clayey soil-cement-rubber crumbles specimen's increases with the increase in curing period. For example, the peak axial load of 7 days cured specimen $S_{92}C_3Rc_5$ in unsoaked condition was 0.178 kN, which increased to 0.185 kN and 0.207 after 14 and 28 days of curing, respectively. The curves of soaked specimens as presented in Figs 5.7, 5.8, and Appendix (Figs. A5 to A8) have also shown the similar trend of increase in peak load with the increase in curing period. Study of Fig. 5.5, 5.6, and Appendix (Figs. A1 to A6) further reveals an increase in deformation at failure with the increase in curing period. For example, deformation at failure of 7 day unsoaked specimen $S_{92}C_3Rc_5$ was 0.004 m, which increased to 0.0045 m with the change in curing period to 14 and 28 days, respectively. Similar trend of increase in deformation with the increase in curing period was observed for soaked specimens as shown in Figs. 5.7 and 5.8 and Appendix (Figs. A5 to A8).

5.3.2 Absolute toughness in compression

Absolute toughness, an indicator of the total energy absorption capacity of the composite has been determined by calculating the area of axial load-deformation curve upto failure as shown in Fig. 4.7of chapter 4. The values of absolute toughness of clayey soil mixed with 3% and 6% cement and 0%. 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured at 7, 14, and 28 days are shown in Table 5.1 for both unsoaked and soaked conditions.

It is observed from Table 5.1 that absolute toughness of clayey soil increases with the increase in cement content. For example, 28 days' absolute toughness of unsoaked specimen $S_{97}C_3Rc_0$ was 0.000356 kN.m, which increased to 0.000951 kN.m for specimen $S_{94}C_6Rc_0$. The absolute toughness of cemented clay increases with the increase in rubber content upto 5%. For example, from Table 5.1, the absolute toughness of 28 days cured specimen $S_{91.5}C_6Rc_{2.5}$ was 0.000707 kN.m, which increased to a value of 0.000721 kN.m for specimen $S_{89}C_6Rc_5$. Although, it is lower than the cement stabilized clay. Further incorporation of rubber crumbles in cement stabilized clayey soil decreases the absolute toughness. For example, the absolute toughness of 3% cemented clay containing 5.0% rubber and 6% cemented clay containing 5.0% rubber was 0.000420 kN.m and 0.000721 kN.m, which decreased to 0.00024 kN.m and 0.00038 kN.m for the same mix containing 10% rubber, respectively. Table 5.1 further shows an increase in absolute toughness of the clayey soil-cement-rubber crumbles mixtures with the increase in curing period. For example, for specimen $S_{94}C_6Rc_0$, a value of absolute toughness of 0.000788 kN.m at 7 days of curing increased to 0.000865 kN.m and 0.000951 kN.m with the increase in curing period to 14 and 28 days, respectively. Similar trend of increase in absolute toughness for soaked clayey soil-cement-rubber crumbles specimens were observed with the increase in cement content and curing period as evident in Table 5.1. For example, 28 days' absolute toughness of soaked specimen $S_{92}C_3Rc_5$ was 0.0000938 kN.m, which increased to 0.000388 kN.m for specimen$S_{89}C_6Rc_5$. The absolute toughness of 7 days cured soaked specimen $S_{92}C_3Rc_5$ was

0.000055 kN.m, which increased to 0.0000881 kN.m and 0.000118 kN.m with the change in curing period to 14 and 28 days.

Table 5.1 Absolute toughness of clayey soil mixed with cement and rubber crumbles

Cement Content (%)	**Curing period (days)**	**Absolute toughness (kN.m x 10^{-4})**									
		Unsoaked condition					**Soaked condition**				
		Rubber crumbles content (%)					**Rubber crumbles content (%)**				
		0	**2.5**	**5**	**7.5**	**10**	**0**	**2.5**	**5**	**7.5**	**10**
3	7	1.872	2.147	3.441	1.967	1.358	0.418	0.553	NA	NA	NA
	14	2.158	3.001	4.021	2.646	1.581	1.118	0.881	1.027	NA	NA
	28	3.586	3.345	4.207	3.432	2.475	1.456	1.186	0.938	NA	NA
6	7	7.886	6.665	5.377	3.782	2.519	3.711	2.073	2.667	0.787	0.551
	14	8.656	6.918	6.961	4.960	2.971	4.387	3.179	3.332	1.171	1.303
	28	9.511	7.073	7.213	5.145	3.842	5.874	5.541	3.885	1.863	1.463

***** NA- Not applicable due to disintegration of specimen

5.3.3 Post peak Compression Response

In order to find the significance of rubber crumbles on toughening characteristics especially in the post peak region, the load axis of load-deformation diagram was normalized with respect to peak axial load (designated as P_P), and the deformation axis was normalized with respect to deformation (designated as d_P) occurring at the peak axial load. The variation of normalized load with normalized deformation of clayey soil mixed with 3% and 6% cement and 0%, 2.5%, 5%, 7.5%, and 10% rubber crumbles, cured for 28 days (unsoaked condition) are shown in Figs. 5.10 and 5.11.The normalized load -normalized deformation curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured in humidity controlled room for 28 days followed by immersion in water for 24 hours are shown in Figs. 5.12 and 5.13 (soaked condition).The normalized load -normalized deformation curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured for 7 and 14 days for both unsoaked and soaked condition are shown in Appendix (Figs. A9 to A16).The effect of inclusion of rubber crumbles on normalized load -normalized deformation behaviour of clayey soil has already been discussed in section 4.3.3 of chapter 4.

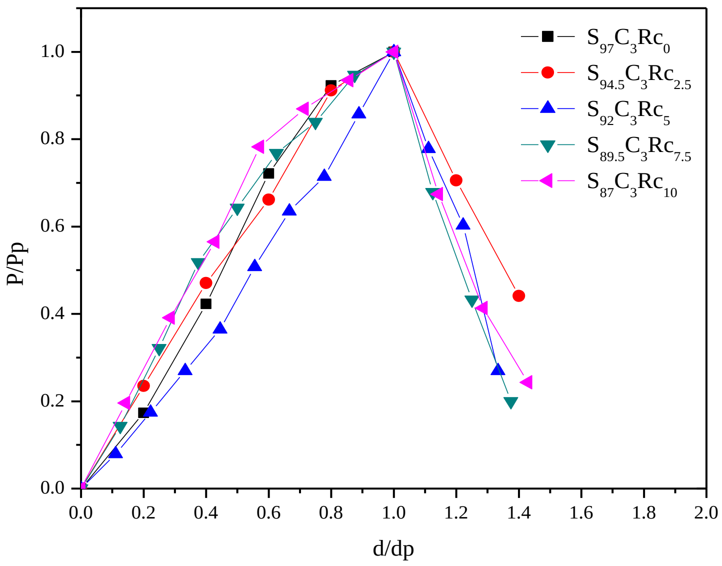


Fig. 5.10 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 28 days (Unsoaked condition)

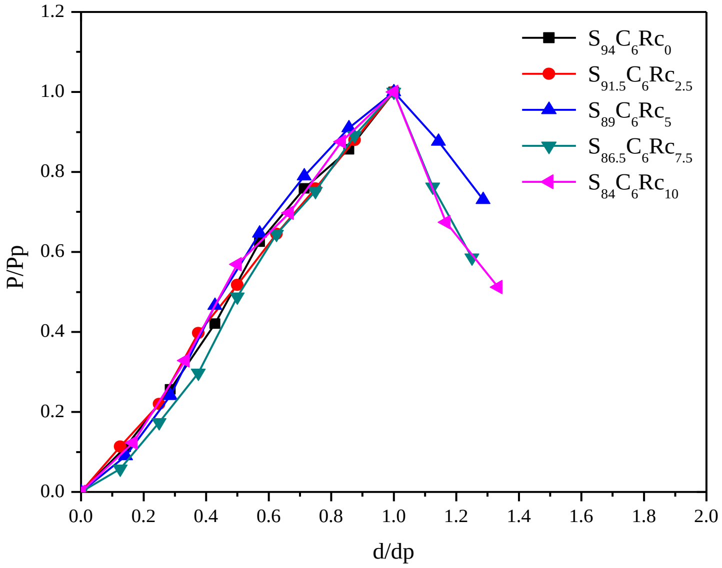


Fig. 5.11 Normalized axial load- deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 28 days (Unsoaked condition)

The study of Figs. 5.10 and 5.11 reveal the sharp drop in post peak load of clay incorporated with 3% and 6% cement content, respectively. A gradual failure is noticed for the clayey specimens incorporated with both cement and rubber crumbles after obtaining peak in the normalized curve. The transformation of acute failure of cemented clay to gradual failure of cemented clay incorporated with rubber crumbles is an indicative of change in the behaviour from brittle to ductile. The possible reasons of the change in behaviour of composite from brittle to ductile are (i) reinforcement effect produced by rubber crumbles, which restrain the cracking; (ii) rubber crumbles are elastic in nature and expected to be prevented from generating and growing cracks by the elastic reaction, which is generated from rubber crumbles during compression.

Further curves of clayey soil-cement-rubber crumbles specimens cured for 7 and 14 days are included in Appendix (Figs. A9 to A12) for unsoaked condition have also shown similar gradual decline after attainment of peak in the normalized load-deformation curve. Beside this, soaked specimens of clayey soil-cement-rubber crumbles mixtures shown in Figs. 5.12 and 5.13 and Appendix (Figs. A13 to A16) have also shown similar behaviour as that of unsoaked specimens.

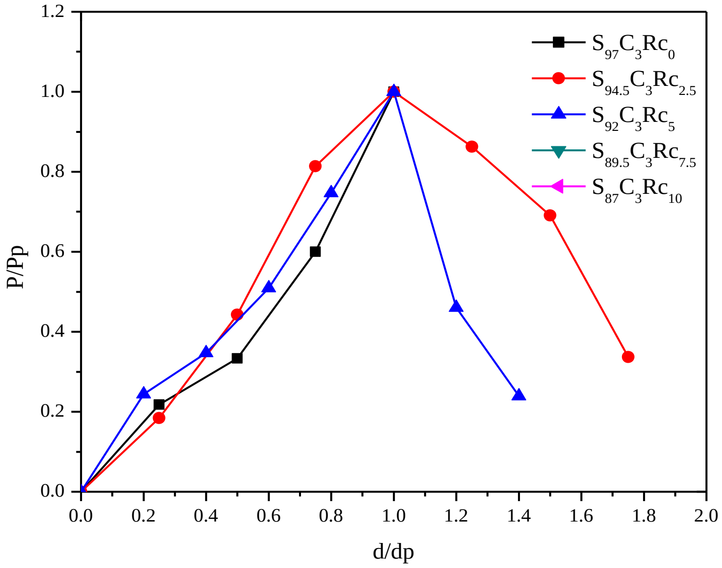


Fig. 5.12 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 28 days (Soaked condition)

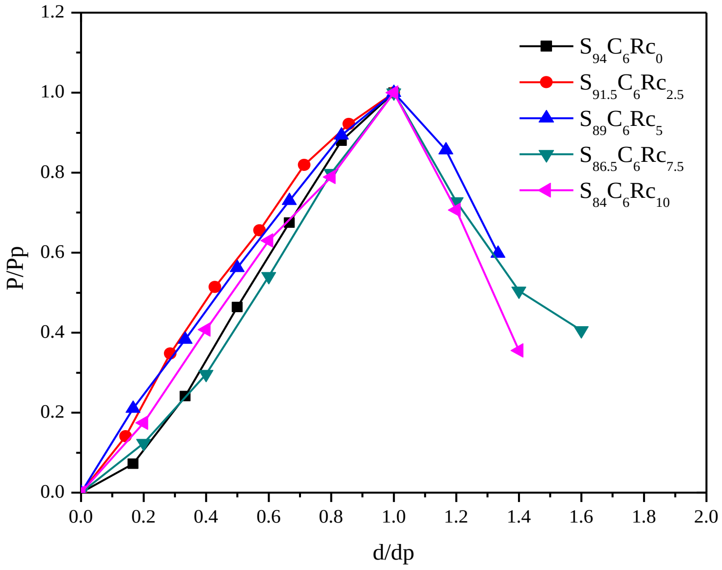


Fig. 5.13 Normalized axial load- deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 28 days (Soaked condition)

5.3.4 Toughness Index in unconfined compression

Further, to focus only on the post peak behaviour under compression and to compare the performance of the clayey soil-cement-rubber crumbles mixtures withthat of an elastic – perfectly material, a dimensionless toughness index (TI) as reported by Sobhan and Mashnad (2002) was calculated, which has already been discussed in section 4.3.4 of chapter 4. The toughness index in compression was calculated up to a maximum of 0.0055 m of axial deformation. The values of toughness index of clayey soil mixed with 3% and 6%cement and 0%. 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured at 7, 14, and 28 days are shown in Table 5.2 for both unsoaked and soaked conditions.

It can be seen from Table 5.2 that the value of TI is zero for clayey soil containing 3% and 6% cement, respectively. It is an indication of typical brittle nature of the cemented clay because of no post peak load carrying capacity (as illustrated in Figs. 5.10 and 5.11). The toughness index of cemented clay increases with the increase in rubber crumbles content up to 5%, further inclusion of rubber crumbles decreases the toughness index. For example, TI of the 3% cemented clay containing 5.0% rubber and 6% cemented clay containing 5.0% rubber crumbles was0.693 and 0.435, which decreased to 0.421 and 0.238 for the same mix containing 10% rubber crumbles, respectively. A study of Table 5.2 further reveals an increase in toughness index with the increase in curing period. For example, for specimen $S_{89}C_6Rc_5$, a value of toughness index of 0.621 at 7 days of curing increased to 0.671 and

0.693 with the increase in curing period to 14 and 28 days. Similar observation was made by Guleria and Dutta (2011), where a decrease in toughness index values of the fly ash-lime-gypsum composite mixed with tyre chips were observed with the increase in rubber content. Similar trend of increase in toughness index of soaked clayey soil-cement-rubber crumbles specimens were observed with the increase in cement content and curing period. For example, the 28 days' toughness index of soaked specimen $S_{92}C_3Rc_5$ was 0.296, which increased to 0.331 for specimen $S_{89}C_6Rc_5$. The toughness index of 7 days cured soaked specimen $S_{89}C_6Rc_5$ was 0.168 which increased to 0.211 and 0.331 with the change in curing period to 14 and 28 days. The TI values of unsoaked specimens of clayey soil-cement-rubber crumbles mixtures is more than soaked specimens for a specific amount of rubber and cement content.

Table 5.2 Toughness index of clayey soil mixed with cement and rubber crumbles

Cement Content (%)	**Curing period (days)**	**Toughness index**									
		Unsoaked condition					**Soaked condition**				
		Rubber crumbles content (%)					**Rubber crumbles content (%)**				
		0	**2.5**	**5**	**7.5**	**10**	**0**	**2.5**	**5**	**7.5**	**10**
3	7	0	0.231	0.621	0.530	0.311	0	0.204	NA	NA	NA
	14	0	0.251	0.671	0.570	0.330	0	0.213	0.224	NA	NA
	28	0	0.298	0.693	0.653	0.421	0	0.290	0.317	NA	NA
6	7	0	0	0.195	0.169	0.164	0	0	0.168	0.158	0.122
	14	0	0	0.241	0.212	0.201	0	0	0.211	0.177	0.154
	28	0	0	0.435	0.311	0.238	0	0	0.331	0.322	0.228

***** NA- Not applicable due to disintegration of specimen

5.3.5 Pattern of cracking in compression

The cracking patterns of 28 days cured specimens $S_{97}C_3Rc_0$, $S_{96}C_6Rc_0$, $S_{94.5}C_3Rc_{2.5}$, $S_{92}C_3Rc_5$, $S_{89.5}C_3Rc_{7.5}$, $S_{87}C_3Rc_{10}$, $S_{91.5}C_6Rc_{2.5}$, $S_{89}C_6Rc_5$, $S_{86.5}C_6Rc_{7.5}$, and $S_{84}C_6Rc_{10}$ under compressive load are shown in Figs 5.14(a) to 5.14(j). Fig 5.14(a) shows the several short and narrow tension cracks in specimen $S_{97}C_3Rc_0$. A single straight primary crack that appears throughout the entire specimen of 6% cemented clay can be seen in Fig. 5.14(b). This crack gets wider and finally leads to catastrophic failure with the increase in axial load. It is a gesture of the brittle nature of cemented specimens and may be responsible for no post peak response of cemented clay as shown in Figs. 5.10 and 5.11.

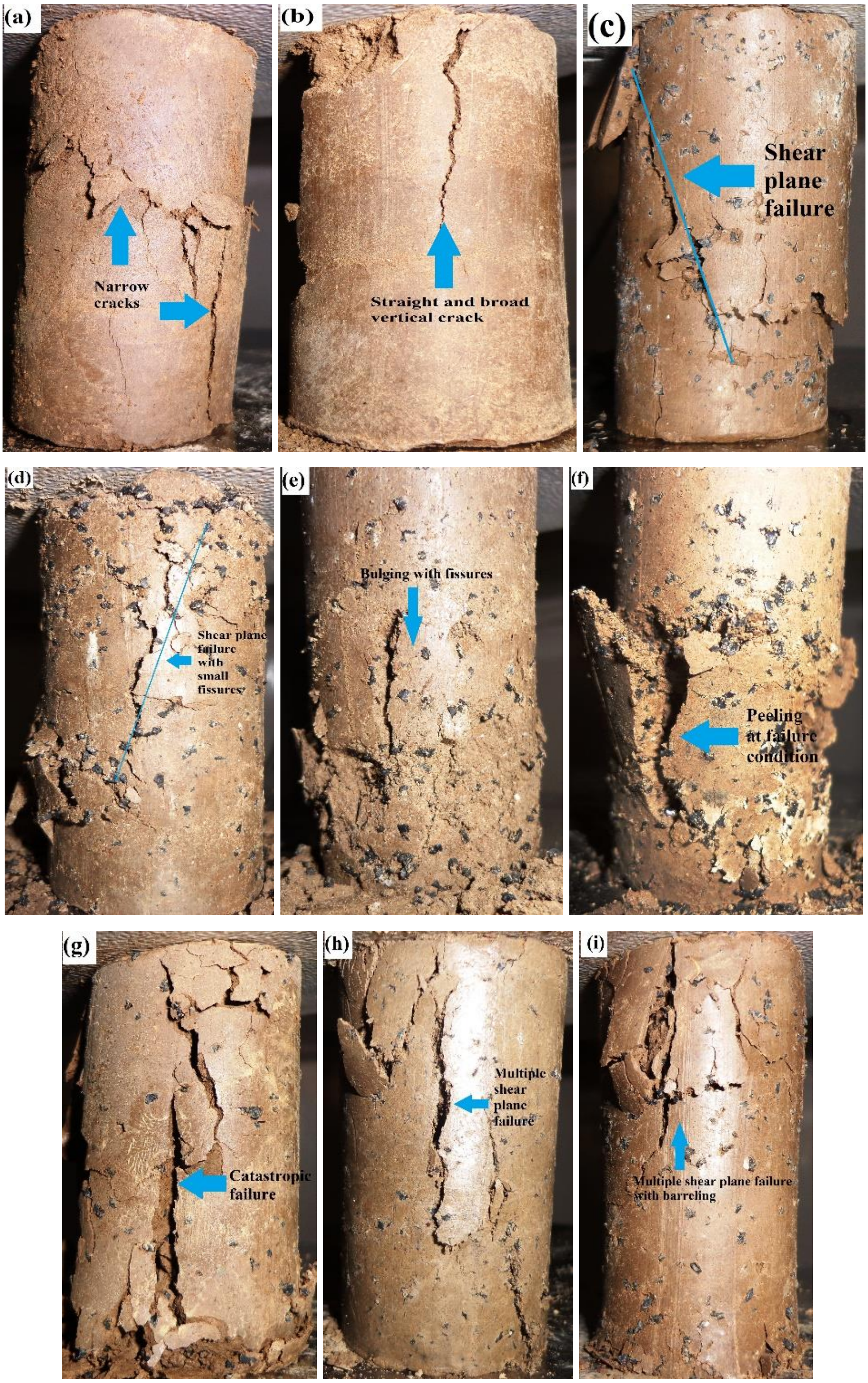


Fig. 5.14 Typical failure patterns of 28 days cured specimens under unconfined compressive strength test (Unsoaked condition)**: (a)** $S_{97}C_3Rc_0$, **(b)** $S_{96}C_6Rc_0$, **(c)** $S_{94.5}C_3Rc_{2.5}$, **(d)** $S_{92}C_3Rc_5$, **(e)** $S_{89.5}C_3Rc_{7.5}$, **(f)** $S_{87}C_3Rc_{10}$, **(g)** $S_{91.5}C_6Rc_{2.5}$, **(h)** $S_{89}C_6Rc_5$, **(i)** $S_{86.5}C_6Rc_{7.5}$

The two shear planes appear diagonally from top to bottom along the length of specimen $S_{94.5}C_3Rc_{2.5}$ is observed as shown in Fig. 5.14(c). Whereas, the specimen $S_{92}C_3Rc_5$ shows similar inclined shear plane at failure with fissures.

In the specimens $S_{89.5}C_3Rc_{7.5}$ and $S_{87}C_3Rc_{10}$, bulging failure with multiple cracks and peeling type failure is observed as shown in Fig. 5.14(d) and 5.14(e). Catastrophic failure is observed for specimen $S_{91.5}C_6Rc_{2.5}$ (Fig. 5.14(e)), which is responsible for the sudden fall in load after peak axial load as illustrated in Fig. 5.11. In contrast to the catastrophic failure of specimen $S_{91.5}C_6Rc_{2.5}$, the failure of specimen $S_{89}C_6Rc_5$ and $S_{86.6}C_6Rc_{7.5}$involve multi-shear planes and multi-shear planes with barrelling in a significant part of the specimen without a distinct failure (Figs. 5.14(f) and 5.14(g)).

Over all, the inclusion of rubber crumbles in cemented clay has resulted into formation of multiple/staggered cracks and consequently prevents complete brittle failure of the composite. It improves the post-peak strength in compression and helps the specimen to bear load after failure.Multiple cracks seen in the specimens may be due to (i) evolution of tensile stress on the surface of rubber particle; (ii) lower young's modulus of the rubber crumbles in comparison to the cemented clay specimens causes dissimilar deformation and helps to induce multiple cracking(Galleria and Dutta 2011). These may be the possible reasons of high absolute toughness and toughness index of cemented specimens containing 5% rubber crumbles. Higher rubber content (> 5%) causes more dissimilar deformation of the specimen, which reduces absolute toughness and toughness index.

Figs. 5.15(a) to 5.15(f) presents the effect of immersion on failure patterns of clayey soil-cement-rubber crumbles specimens. For specimen $S_{94.5}C_3Rc_{2.5}$ and $S_{89}C_6Rc_5$, multiple cracking patterns are observed as shown in Fig. 5.15(a) and 5.15(d). In specimens $S_{92}C_3Rc_5$ and$S_{86.5}C_6Rc_{7.5}$, there is localized appearance of wide multiple cracks all around the specimen surface leading to the peeling of specimen at failure condition (Figs. 5.15(b) and 5.15(e)). In specimen $S_{84}C_6Rc_{10}$, the surficial cracks no longer appear, and the specimen undergoes bulging failure with small fissures (Fig. 5.15(f)) and this may be responsible for the strain-hardening behaviour as shown in Fig. 5.8.

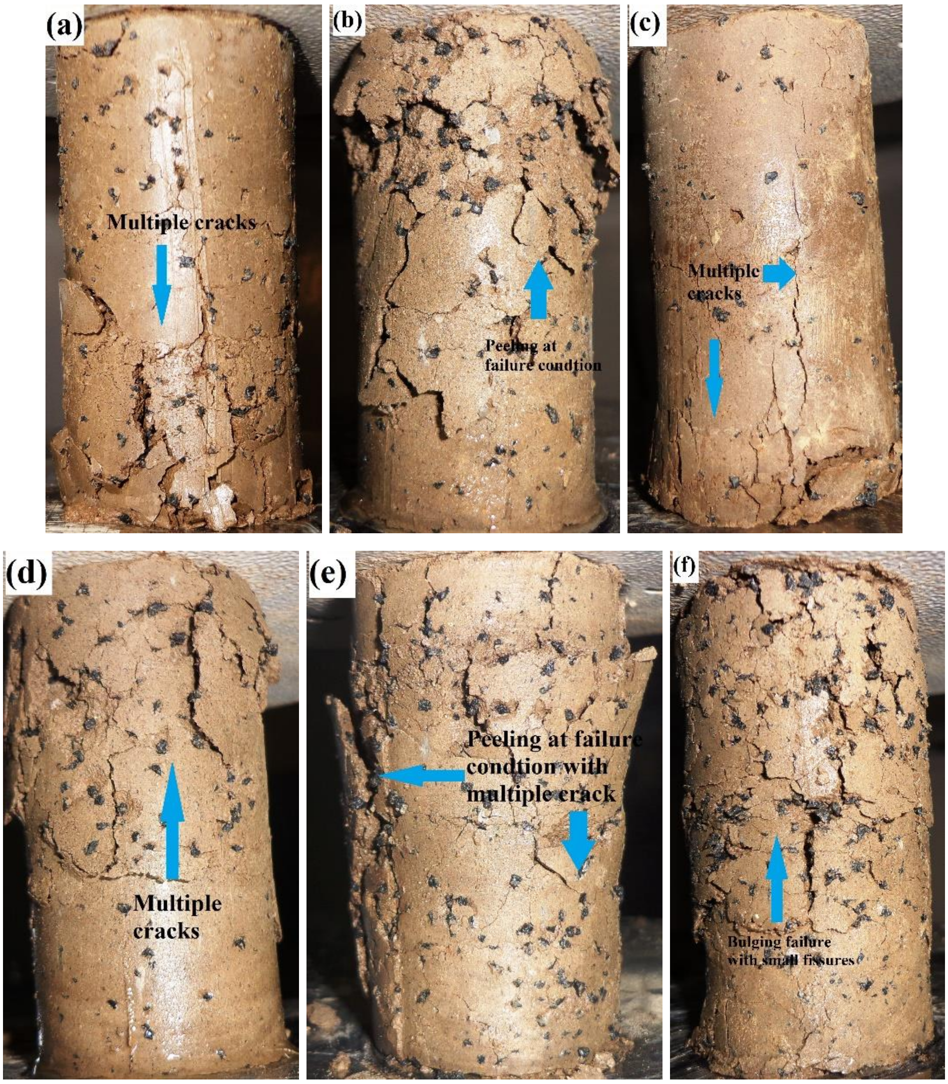


Fig. 5.15 Typical failure patterns of 28 days cured specimens under unconfined compressive strength test (Soaked condition)**: (a)** $S_{94.5}C_3Rc_{2.5}$, **(b)** $S_{92}C_3Rc_5$, **(c)** $S_{91.5}C_6Rc_{2.5}$, **(d)** $S_{89}C_6Rc_5$, **(e)** $S_{86.5}C_6Rc_{7.5}$, **(f)** $S_{84}C_6Rc_{10}$

5.3.6 Unconfined Compressive Strength

The results of unconfined compressive strength of clayey soil-cement-rubber crumbles mixture cured for 7, 14 and 28 days, both unsoaked and soaked condition are shown in Figs. 5.16 to 5.17. Figs. 5.16 and 5.17illustrate that with the increase in cement content and curing time, the unconfined compressive strength of clayey soil-cement-rubber crumbles mixtures increases. For example, the unconfined compressive strength of 7 day cured specimen $S_{89}C_6Rc_5$was 279.54 kPa which increased to 321.32 kPa and 333.85 kPa with the increase in curing period to 14and 28 days, respectively (unsoaked condition). However, the rate of gain of strength is non-linear. It is more during the initial curing and there after it decreases. It is due to the formation of primary cementitious products such as $C_3S_2H_X$ (hydrated gel) and

$Ca(OH)_2$, resulting in short-term hardening of cement clay-rubber composites. The secondary cementitious products such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) formed by the reaction of $Ca^{2+}$with dissolved silica and alumina (by OH^- ions) from the clay minerals. These hydration products crystallize and harden with time and enhance bond strength of the composite. With the immersion in water, the unconfined compressive strength of clayey soil-cement-rubber crumbles mixture decreases as shown in Figs. 5.18 and 5.19. For example, the unconfined compressive strength was 333.85 kPa for specimen $S_{89}C_6Rc_5$ in unsoaked condition, which decreased to 199.66 kPa after immersion.

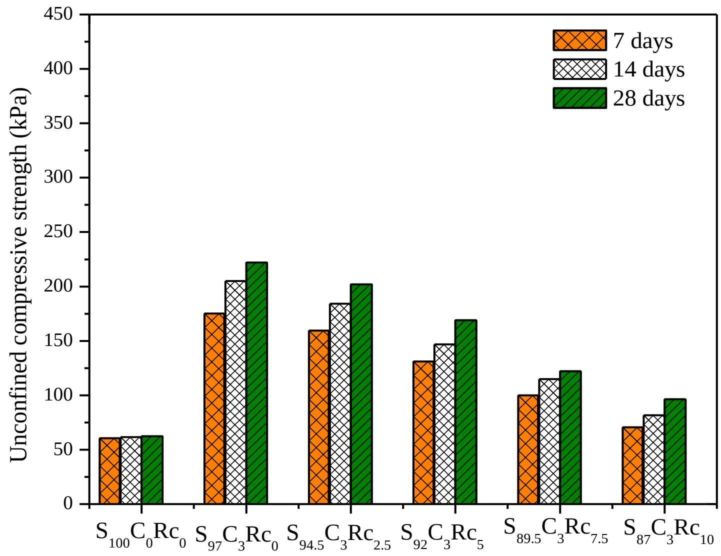


Fig. 5.16 Variation of unconfined compressive strength of clayey soil mixed with 3% cement and rubber crumbles and cured for 7, 14, and 28 days (Unsoaked condition)

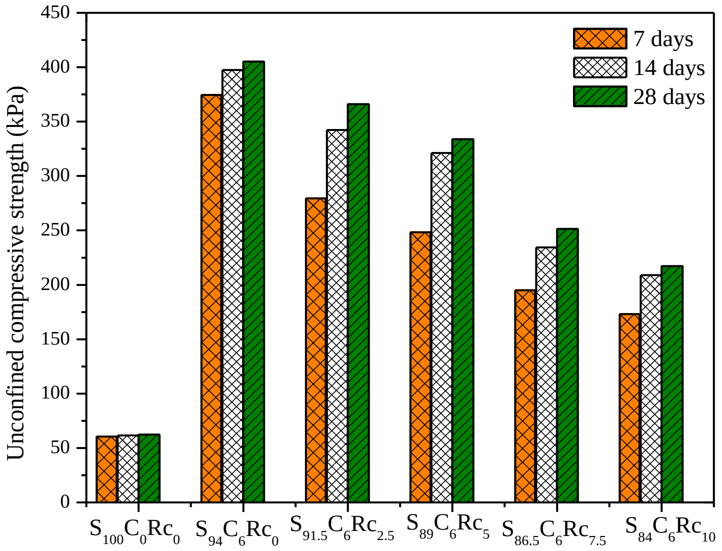


Fig. 5.17 Variation of unconfined compressive strength of clayey soil mixed with 6% cement and rubber crumbles and cured for 7, 14, and 28 days (Unsoaked condition)

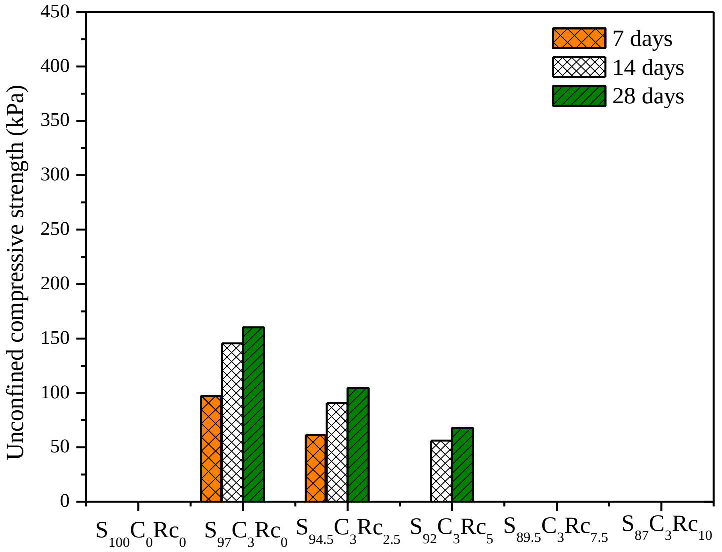


Fig. 5.18 Variation of unconfined compressive strength of clayey soil mixed with 3% cement and rubber crumbles and cured for 7, 14, and 28 days (Soaked condition)

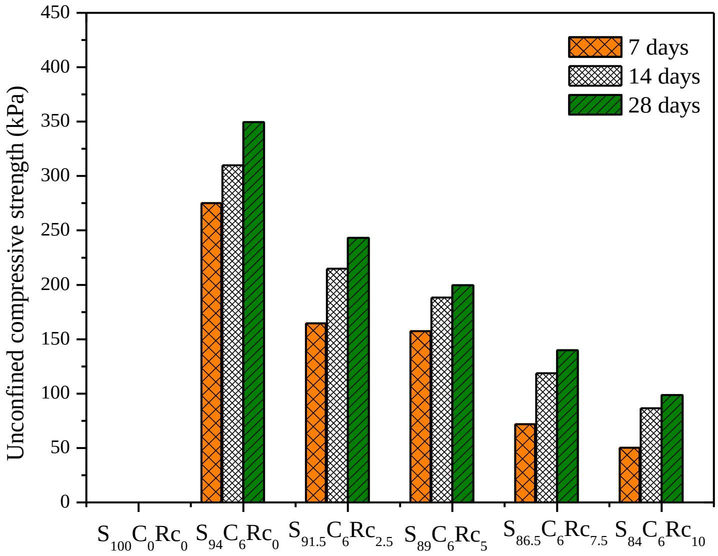


Fig. 5.19 Variation of unconfined compressive strength of clayey soil mixed with 6% cement and rubber crumbles and cured for 7, 14, and 28 days (Soaked condition)

A study of Figs. 5.16 and 5.17 also reveals that the unconfined compressive strength of clayey soil-cement-rubber crumbles mixtures decreases with the increase in rubber crumbles content. For example, the unconfined compressive strength of 28 days cured unsoaked specimen $S_{94.5}C_6Rc_{2.5}$was 366.13 kPa, which decreased to 333.85 kPa, 251.36 kPa, and 217.11 kPa for specimens $S_{89}C_6Rc_5$, $S_{86.5}C_6Rc_{7.5}$, and $S_{84}C_6Rc_{10}$, respectively. This decrease in unconfined compressive strength of the clayey soil-cement-rubber crumbles mixtures with the increase in rubber crumbles content may attributed to the fact that rubber crumbles being non-polar in nature have tendency to entrap air during mixing resulting reduction in unconfined compressive strength of the specimen. Further, rubber crumbles would also act as voids within the specimen and carries negligible load in comparison to hardened cemented clay. The dissimilar rate of deformability between rubber crumbles and hardened cemented clay leads to premature cracking which results reduction in unconfined compressive strength of the specimen. At higher rubber content (≥ 5%), the rate of loss in strength is more, which is due to the accumulation of rubber particles that leads to poor interaction between cemented clay -rubber particles surface as shown in Fig. 5.20. Similar trend of decrease in unconfined compressive strength with the increase in rubber crumbles content was observed for soaked specimens. However, the rate of loss of unconfined compressive strength is even more compared to the unsoaked specimens.

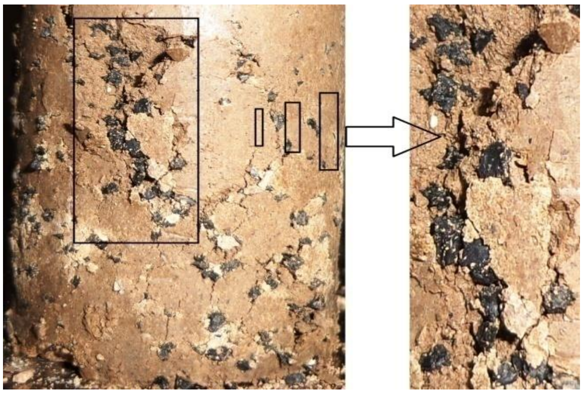


Fig. 5.20 Accumulation of rubber crumbles in the specimen

5.4. TENSION BEHAVIOUR

5.4.1. Load-Diametral Deformation Response

In order to investigate the behaviour of cemented clay incorporated with varying rubber crumbles content under tensile load, the tensile load is plotted against diametral deformation. The tensile load-diametral deformation response of cement stabilized clayey soil incorporated with/without 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured for 28 days are shown in Figs. 5.21 and 5.22 (unsoaked condition). The tensile load-diametral deformation curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured in humidity controlled room for 28 days followed by immersion in water for 24 hrs are shown in Figs. 5.23 and 5.24(soaked condition). The curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured for 7 and 14 days for both unsoaked and soaked condition are shown in Appendix (Figs. A17 to A24). The effect of inclusion of rubber crumbles on tensile load-diametral deformation behaviour of clayey soil has already been discussed in section 4.4.1 of chapter 4.

The effect of inclusion of cement (3% and 6%) on tensile load-diametral deformation behaviour of clay soil specimens cured for 28 days are shown in Figs. 5.21 and 5.22. The peak tensile load of clayey soil increases with the increase in cement content. For example, for specimen $S_{97}C_3Rc_0$, the peak axial load was 0.395 kN, which increased to 0.721 kN, for specimen $S_{94}C_6Rc_0$. The reason of increase in tensile strength has already been explained in the section 5.3.1. Similar trend of increase in peak tensile load was observed for the soaked specimens $S_{97}C_3Rc_0$and $S_{94}C_6Rc_0$ with the increase in percentage of cement as shown in Fig. 5.23 and 5.24, respectively. Figs. 5.21 to 5.24 shows that the peak value of tensile load of cemented clay specimen’s drop to zero abruptly indicate the brittle behaviour of the specimens. A close examination of Figs. 5.5 and 5.6 and Figs. 5.21 and 5.22 reveals that the cementitious clay can take larger load in tension as compared to compression indicates that cementation of clay is more efficient under tension.

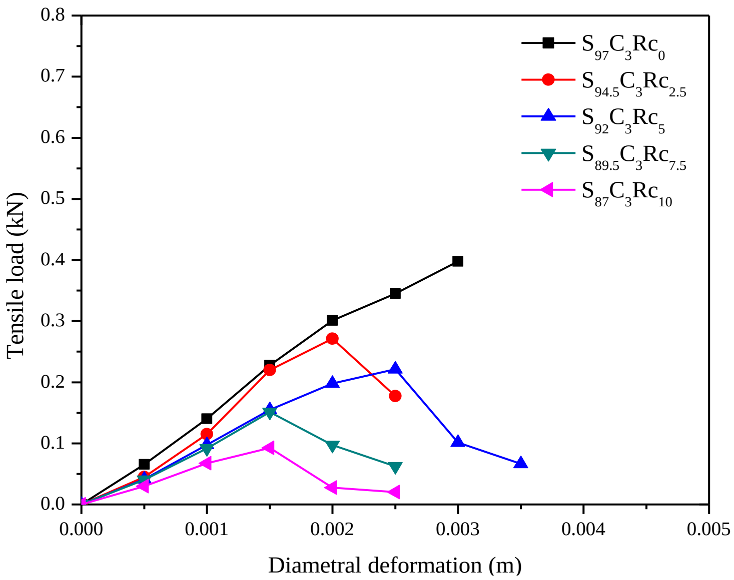


Fig. 5.21 Tensile load-diametral deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 28 days (Unsoaked condition)

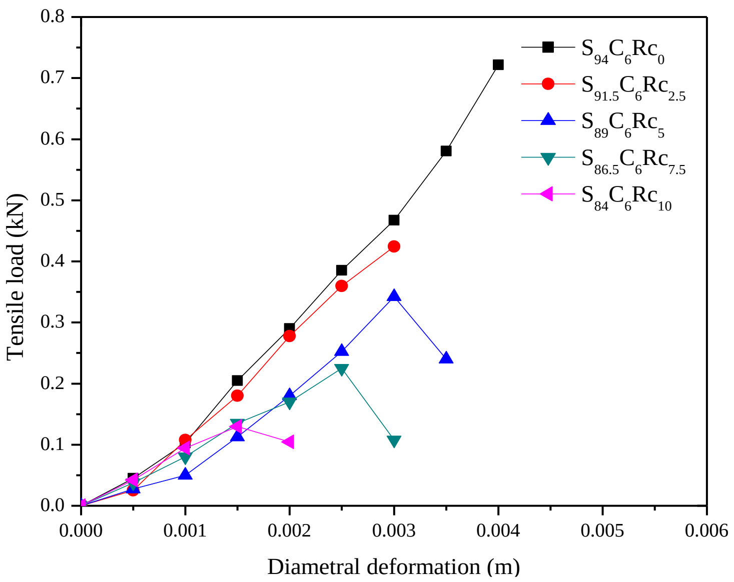


Fig. 5.22 Tensile load-diametral deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 28 days (Unsoaked condition)

The combined effect of cement and rubber crumbles on tensile load-diametral deformation behaviour of clayey soil cured for 28 days is delineated in Figs. 5.21 and 5.22. The peak tensile loads in tension are on the same guideline of peak axial loads in compression. The peak tensile load of clayey soil containing 3% and 6% cement decreases with the increase in content of rubber crumbles. For example, for unsoaked specimen $S_{97}C_3Rc_0$, the peak tensile load was 0.397 kN, which decreased to 0.271 kN, 0.223 kN, 0.151 kN, and 0.092 kN for specimens $S_{94.5}C_3Rc_{2.5}$, $S_{92}C_3Rc_5$, $S_{89.5}C_3Rc_{7.5}$, and$S_{87}C_3Rc_{10}$, respectively. The reason for decreases in tensile strength has already been explained in the section 5.3.1. Similar trend of reduction in peak tensile load was observed for the soaked specimens of clayey soil-cement-rubber crumbles mixtures with the increase in rubber crumbles content as shown in Figs. 5.23 and 5.24. For example, for soaked specimen $S_{94}C_6Rc_0$, the peak tensile load was 0.412 kN, which decreased to 0.306 kN, 0.267 kN, 0.187 kN, and 0.105 kN for specimens $S_{91.5}C_6Rc_{2.5}$, $S_{89}C_6Rc_5$, $S_{86.5}C_6Rc_{7.5}$, and$S_{84}C_6Rc_{10}$, respectively. The reason of reduction in tensile load of soaked specimens has already been discussed in the section 5.3.1.

The peak diametral deformations of clayey soil-cement-rubber crumbles mixtures under tensile load are on the same guideline of peak axial deformation in compression. Examination of Figs. 5.21 and 5.22 reveal that the diametral deformation of clayey soil stabilized with cement is more than that of specimen containing both rubber crumbles and cement. For example, for specimen $S_{97}C_3Rc_0$ and $S_{94}C_6Rc_0$, the diametral deformation corresponding to peak tensile load was 0.003 m and 0.004 m, which decreased to 0.0025 m and 0.003 m for specimen$S_{92}C_3Rc_5$ and $S_{89}C_6Rc_5$, respectively. A close examination of Figs. 5.21 and 5.22 reveal that the increase in diametral deformation was highest with inclusion of 5% rubber crumbles in cement stabilized clayey-rubber crumbles mixtures. For example, for unsoaked specimen $S_{92}C_3Rc_5$, the diametral deformation was 0.0025 m, which decreased to 0.002 m, 0.0015m and 0.0015 m for specimens $S_{94.5}C_3Rc_{2.5}$, $S_{91.5}C_3Rc_{7.5}$, and $S_{87}C_3Rc_{10}$, respectively. A similar trend was observed for soaked specimens of clayey soil-cement-rubber crumbles mixtures as well shown in Figs. 5.23 and 5.24.

A close examination of Fig. 5.21, Fig. 5.22 and Appendix (Figs. A17 to A20) reveals that the peak tensile load of clayey soil-cement-rubber crumbles specimen's increases with the increase in curing period. For example, the peak tensile load of 7 days cured specimen $S_{92}C_3Rc_5$ in unsoaked condition was 0.175 kN, which increased to 0.205 kN and 0.221 kN after 14 and 28 days of curing, respectively. The curves of soaked specimens as shown in Figs 5.23 and 5.24 and Appendix (Figs. A21to A24) have also shown the similar trend of increase in peak tensile load with the increase in curing period.

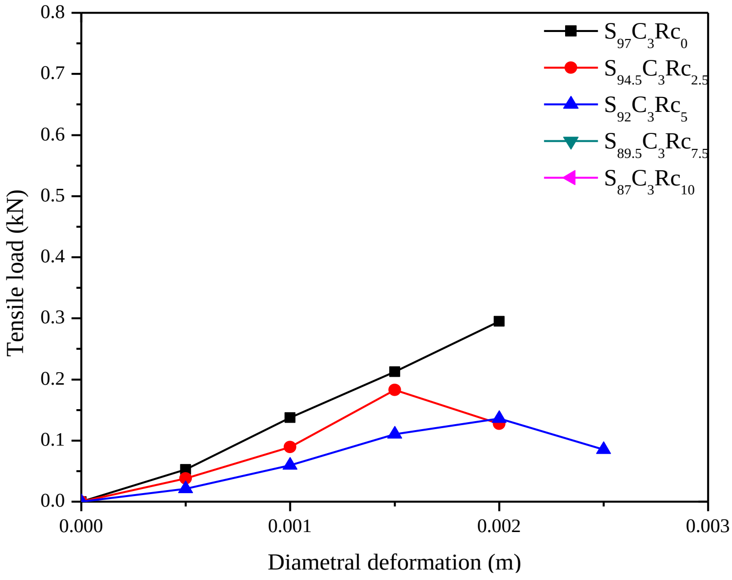


Fig. 5.23 Tensile load-diametral deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 28 days (Soaked condition)

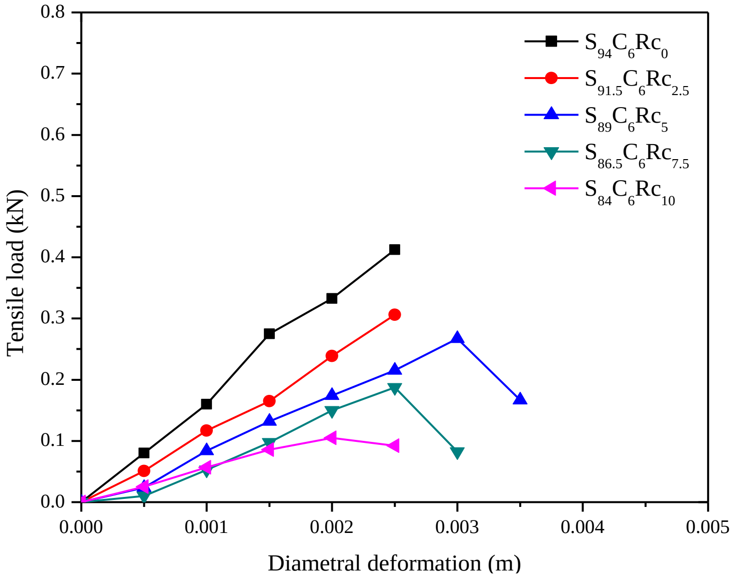


Fig. 5.24 Tensile load-diametral deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 28 days (Soaked condition)

Study of Fig. 5.21, Fig. 5.22 and Appendix (Figs. A17 to A20) further reveals that the diametral deformation of clayey soil-cement-rubber crumbles mixture increases with the increase in curing period. For example, diametral deformation at failure for 7 and 14 day cured unsoaked specimen $S_{92}C_3Rc_5$ was 0.002 m, which increased to 0.0025 mm with the change in curing period to 28 days. Similar trend of increase in the diametral deformation with the increase in curing period was observed for soaked specimens as shown in Figs. 5.23 and 5.24 and Appendix (Figs. A21 to A24).

5.4.2. Absolute toughness in tension

Absolute toughness, an indicator of the total energy absorption capacity of composite has been determined by calculating the area of the tensile load-diametral deformation curve upto failure as shown in Fig. 4.18 of chapter 4. The values of absolute toughness of clayey soil mixed with 3% and 6%cement and 0%. 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured at 7, 14, and 28 days are shown in Table 5.3 for both unsoaked and soaked conditions.

An examination of Table 5.3 shows that the absolute toughness of clayey soil increases with the increase in cement content. For example, the 28 days' absolute toughness of specimen $S_{97}C_3Rc_0$ was 0.000635 kN.m, which increased to 0.00892 kN.m for specimen $S_{94}C_6Rc_0$. The absolute toughness of cemented clay increases with the increase in rubber crumbles content upto 5%. For example, from Table 5.3, the absolute toughness of 28 days cured specimen $S_{94.5}C_3Rc_{2.5}$ was 0.000284 kN.m, which increased to a value of 0.000303 kN.m for specimen $S_{92}C_3Rc_5$. Although, it is lower than the cement stabilized clay. Further incorporation of rubber crumbles in cement stabilized clayey soil decreases the absolute toughness. Whereas, a continuous reduction in absolute toughness is observed for the clayey soil-rubber crumbles mixture stabilized with 6% cement. For example, from Table 5.3, the absolute toughness of 28 days cured specimen $S_{91.5}C_6Rc_{2.5}$ was 0.000558 kN.m, which decreased to a value of 0.000396 kN.m, 0.000267 kN.m, and 0.000101 kN.m for specimens $S_{89}C_6Rc_5$, $S_{86.5}C_6Rc_{7.5}$, and $S_{84}C_6Rc_{10}$, respectively. The rate of decrement in absolute toughness of clayey soil-cement-rubber crumbles mixtures under tensile load is greater than compression. Table 5.3 further shows an increase in the absolute toughness of clayey soil-cement-rubber crumbles mixtures with the increase in curing period. For example, for specimen $S_{94}C_6Rc_0$, a value of absolute toughness of 0.000324 kN.m at 7 days of curing increased to 0.000437 kN.m and 0.000558 kN.m with the increase in curing period to 14 and 28 days. Similar trend of increase in absolute toughness of soaked clayey soil-cement-rubber crumbles specimens were observed with the increase in cement content and curing period as evident in Table 5.3. For example, the 28 days' absolute toughness of soaked specimen $S_{92}C_3Rc_5$ was 0.000129 kN.m, which increased to 0.0003815 kN.m for specimen$S_{89}C_6Rc_5$. The absolute toughness of 7 days cured soaked specimen $S_{89}C_6Rc_5$ was 0.000223 kN.m, which increased to0.000323 kN.m and 0.000381 kN.m, with the change in curing period to 14 and 28 days.

Table 5.3 Absolute toughness in tension of clayey soil mixed with cement and rubber crumbles

Cement Content (%)	Curing period (days)	Absolute toughness (kN.m x 10^{-4})									
		Unsoaked condition					Soaked condition				
		Rubber crumbles content (%)					Rubber crumbles content (%)				
		0	**2.5**	**5**	**7.5**	**10**	**0**	**2.5**	**5**	**7.5**	**10**
3	7	4.080	1.339	1.702	0.907	0.442	2.095	0.850	0.966	NA	NA
	14	6.094	1.611	1.987	1.080	0.568	2.537	1.170	1.256	NA	NA
	28	6.351	2.843	3.034	1.039	0.718	2.749	1.094	1.293	NA	NA
6	7	6.224	3.243	2.998	2.015	0.548	3.572	1.944	2.231	1.231	0.922
	14	8.062	4.437	3.562	2.355	0.953	4.881	2.431	3.231	1.643	1.092
	28	8.927	5.581	3.968	2.678	1.012	5.268	3.476	3.815	1.954	1.098

***** NA- Not applicable due to disintegration of specimen

5.4.3. Post peak Tensile Response

In order to find out the significance of rubber crumbles on toughening characteristics especially in the post peak tensile region, the load axis of tensile load – diametric deformation diagram was normalized with respect to peak tensile load, and the diametral deformation axis was normalized with respect to deformation occurring at the peak tensile load. The variation of normalized tensile load with normalized diametral deformation of cemented clayey soil mixed with/without 2.5%, 5%, 7.5%, and 10% rubber crumbles, cured for 28 days (unsoaked condition) are shown in Figs. 5.25 and 5.26. The normalized tensile load -normalized daimetral deformation curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured in humidity controlled room for 28 days followed by immersion in water for 24 hrs are shown in Figs. 5.27 and 5.28 (soaked condition).The normalized tensile load-normalized daimetral deformation curves of cement stabilized clayey soil mixed with/without 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured for 7 and 14 days for both unsoaked and soaked condition are shown in Appendix (Figs. A25 to A32).The effect of inclusion of rubber crumbles on normalized tensile load -normalized daimetral deformation behaviour of clayey soil has already been discussed in section 4.4.3 of chapter 4.

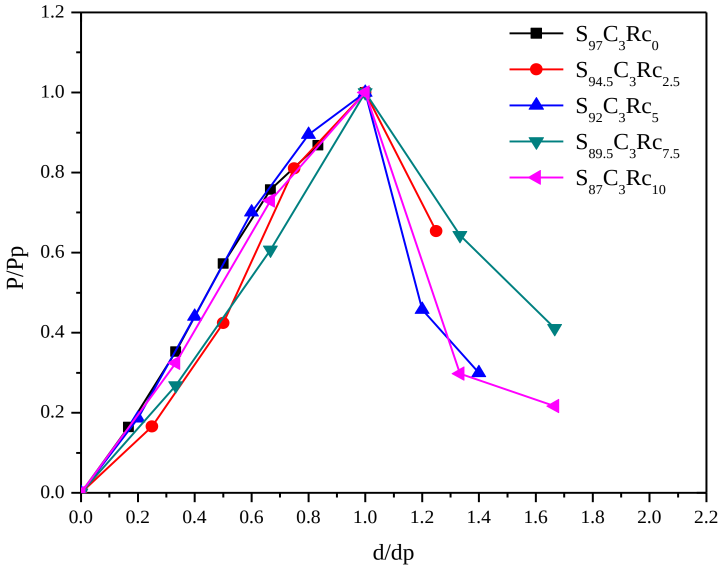


Fig. 5.25 Normalized tensile load-deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 28 days (Unsoaked condition)

An exanimation of Figs. 5.25 and 5.26 reveal a sharp fall in the post peak load of the cemented clay, which is on the same guidelines as that of cemented clay under compressive load. Contrary to the normalized axial load curves of clay incorporated with both cement and rubber crumbles under compressive load, an almost sudden drop in post peak region is seen for the clayey soil-cement-rubber crumbles specimens under tensile load after obtaining the peak. It shows the ineffectiveness of rubber crumbles in improving the behaviour of cemented clay (i.e. brittle to ductile) under tensile loads. This sudden failure of the composite in tension is perhaps due to the sliding of the rubber crumbles in clayey cement matrix, is not restricted by the interfacial mechanical interaction between the rubber crumbles and rest of the composite. Further curves of the clayey soil-cement-rubber crumbles specimens cured for 7 and 14 days included in Appendix (Figs. A25 to A32) for unsoaked condition have also shown similar behaviour after attainment of the peak tensile load in normalized peak tensile load-deformation curves. Beside this, soaked specimens of clayey soil-cement-rubber crumbles mixtures shown in Figs. 5.27 and 5.28 and Appendix (Figs. A29 to A32) have also shown similar behaviour as that of unsoaked specimens.

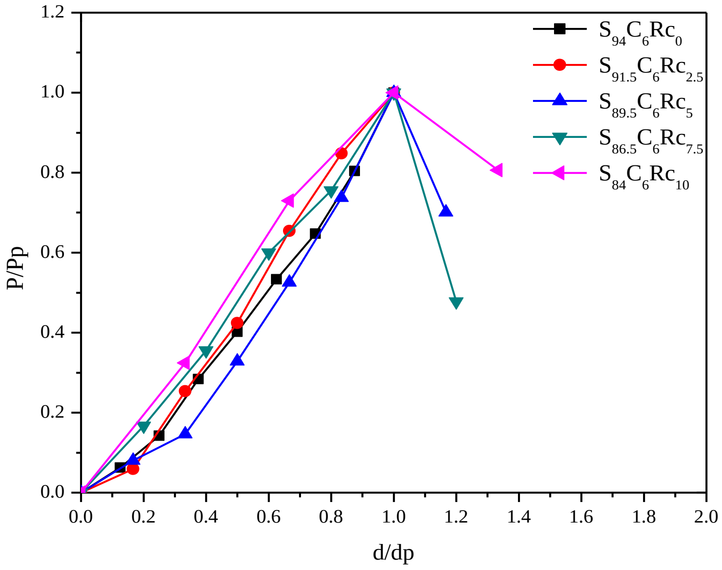


Fig. 5.26 Normalized tensile load-deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 28 days (Unsoaked condition)

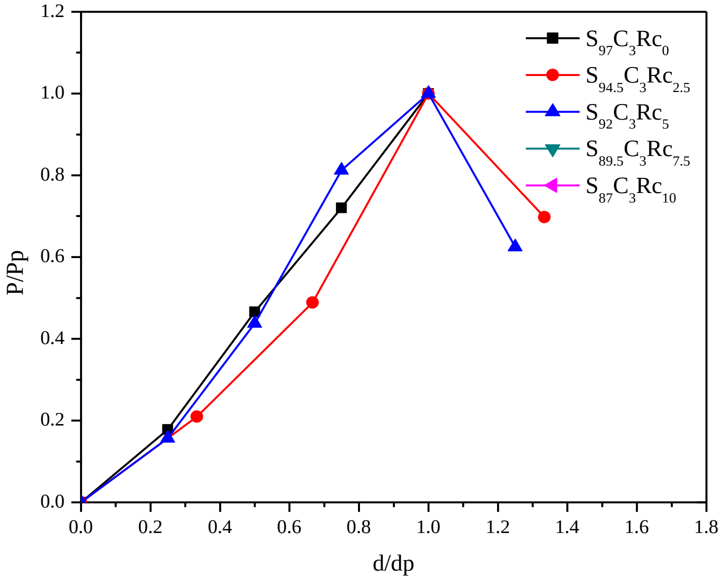


Fig. 5.27 Normalized tensile load-deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 28 days (Soaked condition)

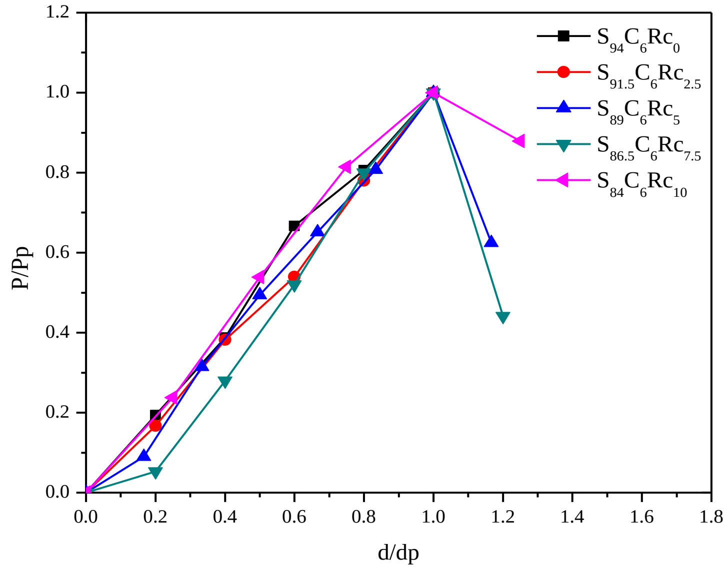


Fig. 5.28 Normalized tensile load-deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 28 days (Soaked condition)

5.4.4. Toughness Index in Tension

In order to specifically find out the significance of clayey soil mixed with 0%, 2.5 %, 5%, 7.5%, and 10% rubber crumbles and 3% and 6% cement in post peak tensile region and to compare their performance with that of an elastic–perfectly material, a dimensionless toughness index in tension (TI) as reported by Sobhan and Mashnad (2002) was calculated. The toughness index has already been defined in the section 4.4.4 of chapter 4. The toughness index in tension was calculated up to a maximum of 0.0055 m of diametral deformation. The values of toughness index of clayey soil mixed with 3% and 6% cement and 0%, 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured at 7, 14, and 28 days are shown in Table 5.4 for both unsoaked and soaked conditions.

It can be seen from Table 5.4 that the value of TI is zero for the cemented clay, which is similar to the behaviour of composite under compressive load. The toughness index of cemented clayey increases continuously with the inclusion of rubber crumbles up to 5%. For example, TI of 28 days cured specimen $S_{94.5}C_3Rc_{2.5}$ was 0.118, which increased to 0.184, for specimens $S_{92}C_3Rc_5$. It decreased to 0.168 and 0.113 for specimens $S_{89.5}C_3Rc_{7.5}$, and $S_{87}C_3Rc_{10}$, respectively. A study of Table 5.4 further reveals an increase in toughness index with the increase in curing period. For example, for specimen $S_{92}C_3Rc_5$, a value of toughness index of 0.155 at 7 days of curing period increased to 0.169 and 0.184 with the increase in curing period to 14 and 28 days. Similar trend of increment in toughness index of soaked clayey soil-cement-rubber crumbles specimens was observed with the increase in curing period. For example, the toughness index of 7 days cured soaked specimen $S_{89}C_6Rc_5$ was 0.117 which increased to 0.120 and 0.162 with change in curing period to 14 and 28 days. The TI values of unsoaked specimens of clayey soil-cement-rubber crumbles mixtures is more than soaked specimens for a specific amount of rubber and cement content.

Table 5.4 Toughness index in tension for clayey soil mixed with cement and rubber crumbles

Cement Content (%)	Curing period (days)	Toughness index									
		Unsoaked condition					Soaked condition				
		Rubber crumbles content (%)					Rubber crumbles content (%)				
		0	**2.5**	**5**	**7.5**	**10**	**0**	**2.5**	**5**	**7.5**	**10**
3	7	0	0.103	0.155	0.115	0.057	0	0.091	NA	NA	NA
	14	0	0.112	0.169	0.125	0.105	0	0.095	0.103	NA	NA
	28	0	0.118	0.184	0.168	0.113	0	0.106	0.116	NA	NA
6	7	0	0	0.135	0.114	0.103	0	0	0.117	0.105	0.092
	14	0	0	0.166	0.121	0.107	0	0	0.120	0.106	0.102
	28	0	0	0.170	0.123	0.112	0	0	0.162	0.120	0.114

***** NA- Not applicable due to disintegration of specimen

5.4.5. Cracking Pattern in Tension

Figs. 5.29(a) to 5.29(f)show the cracking patterns of the 28 days cured specimens $S_{97}C_3Rc_0$, $S_{94}C_6Rc_0$, $S_{94.5}C_3Rc_{2.5}$, $S_{92}C_3Rc_5$, $S_{91.5}C_6Rc_{2.5}$, $S_{89}C_6Rc_5$, and $S_{86.5}C_6Rc_{7.5}$ under tensile load. An examination of Figs. 5.29(a) and 5.29(b) show the development of vertical cracks in cemented clay specimen and responsible for catastrophic failure. The sudden failure is accountable for no post peak strength of cemented clay under tensile loads. Similarly, the specimens $S_{94.5}C_3Rc_{2.5}$, $S_{92}C_3Rc_5$, $S_{91.5}C_6Rc_{2.5}$, $S_{89}C_6Rc_5$, and $S_{86.5}C_6Rc_{7.5}$achieved failure along the central vertical plane as shown in Fig. 5.29(c) to 5.29(f). The specimens of clayey soil-cement-rubber crumbles mixture split into two halves with development of small fissures as shown in Fig. 5.29(f).

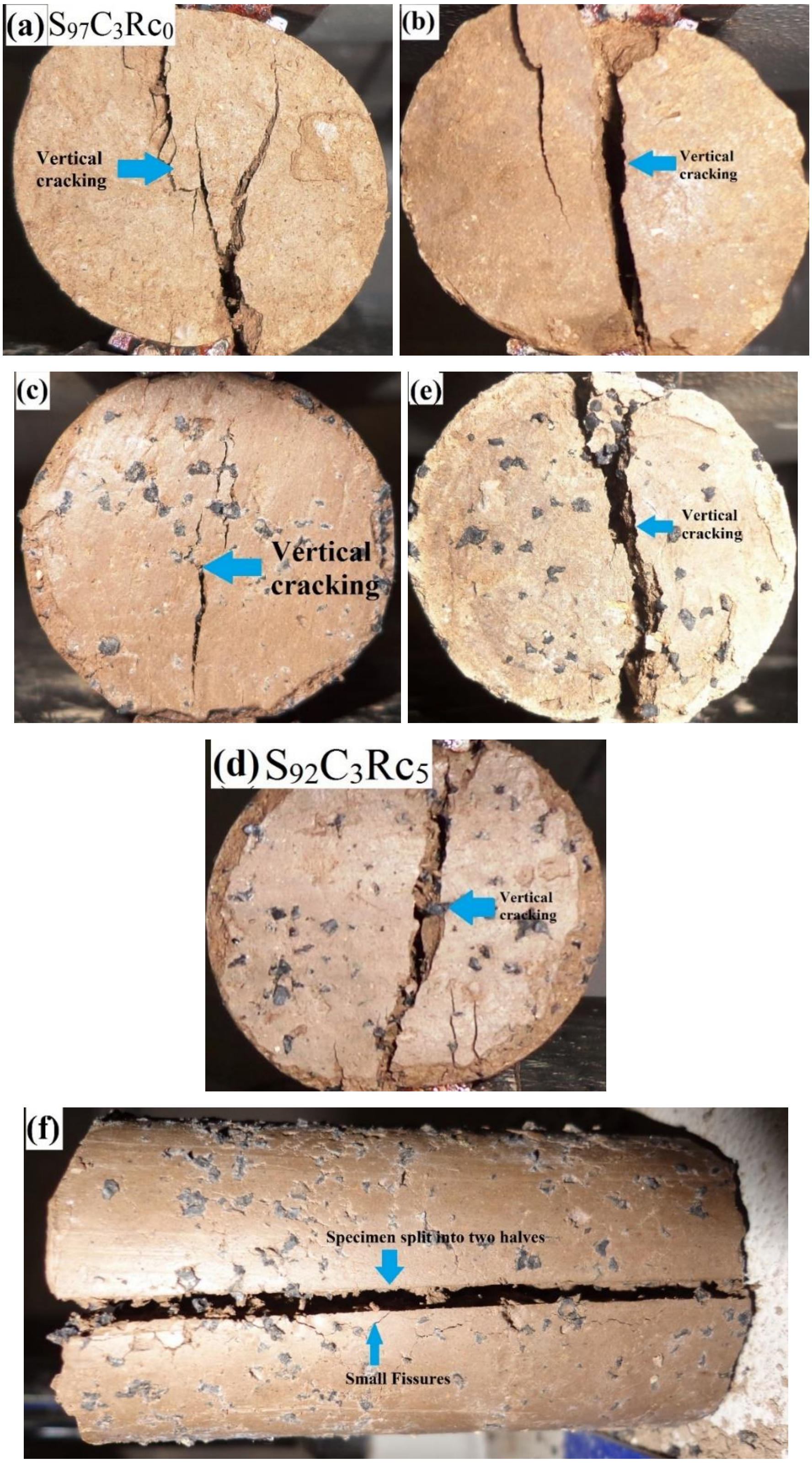


Fig. 5.29 Typical failure patterns of 28 days cured specimens under split tensile strength test (Unsoaked condition)**:** **(a)** $S_{97}C_3Rc_0$, **(b)** $S_{96}C6Rc_0$, **(c)** $S_{94.5}C_3Rc_{2.5}$, **(d)** $S_{92}C_3Rc_5$, **(e)** $S_{89}C_6Rc_5$, **(f)** $S_{86.5}C_6Rc_{7.5}$

The specimens of clayey soil containing cement and rubber crumbles show an improvement in post-peak region in tension as shown in Figs. 5.25 and 5.26, which is insignificant. This marginal improvement in post-peak region can be attributed to the formation of small fissure near the failure plane as evident in Fig. 5.29(f), which helps to restrict some amount of load after attaining peak tensile load. The formation of small fissures at the failure plane may be attributed to the lower young's modulus of rubber crumbles in comparison to hardened cemented clayey soil causes dissimilar deformation and thus induces fissures in the specimens. Contrary to the unsoaked specimens, the soaked specimens of clayey soil-cement-rubber crumbles mixtures shows multiple cracks as shown in Fig. 5.30.

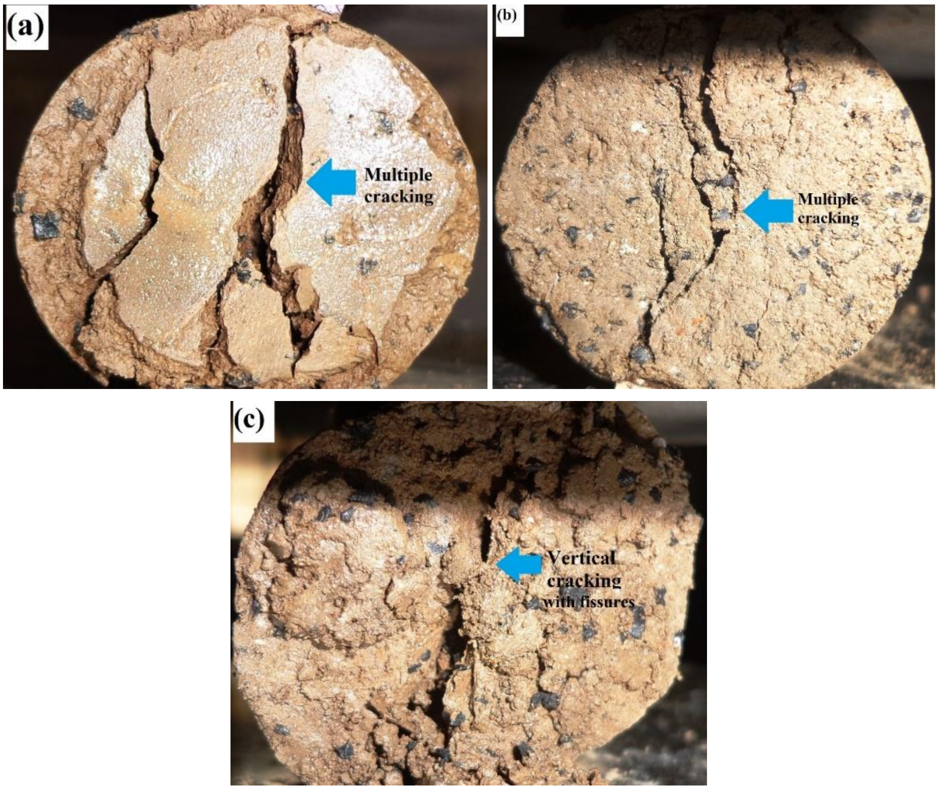


Fig. 5.30 Typical failure patterns of 28 days cured specimens under split tensile strength test (Soaked condition): **(a)** $S_{94.5}C_3Rc_{2.5}$, **(b)** $S_{89}C_6Rc_5$, **(c)** $S_{86.5}C_6Rc_{7.5}$

5.4.6. Split Tensile Strength

The result of split tensile strength of clayey soil-cement-rubber crumbles mixtures cured for 7, 14 and 28 days both unsoaked and soaked condition are shown in Figs. 5.31 to 5.34.

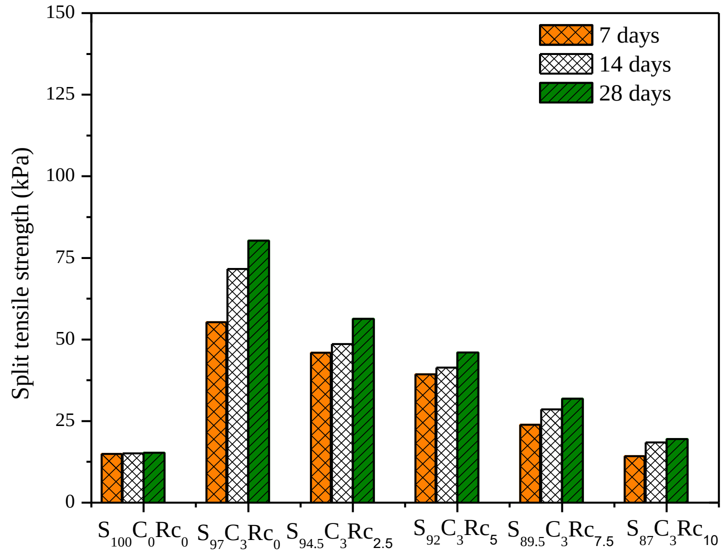


Fig. 5.31 Variation of split tensile strength of clayey soil mixed with 3% cement and rubber crumbles and cured for 7, 14, and 28 days (Unsoaked condition)

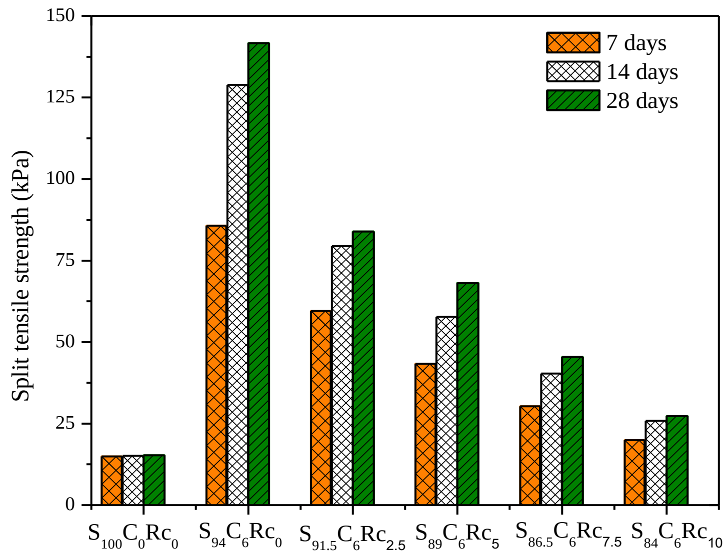


Fig. 5.32 Variation of split tensile strength of clayey soil mixed with 6% cement and rubber crumbles and cured for 7, 14, and 28 days (Unsoaked condition)

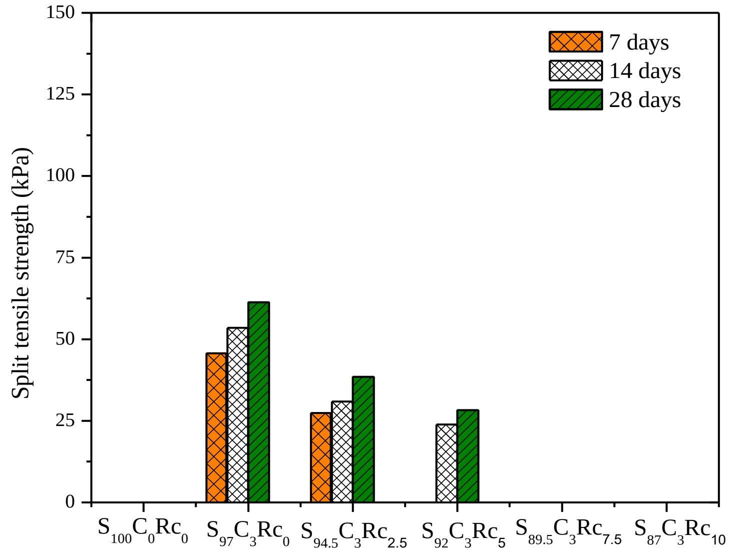


Fig. 5.33 Variation of split tensile strength of clayey soil mixed with 3% cement and rubber crumbles and cured for 7, 14, and 28 days (Soaked condition)

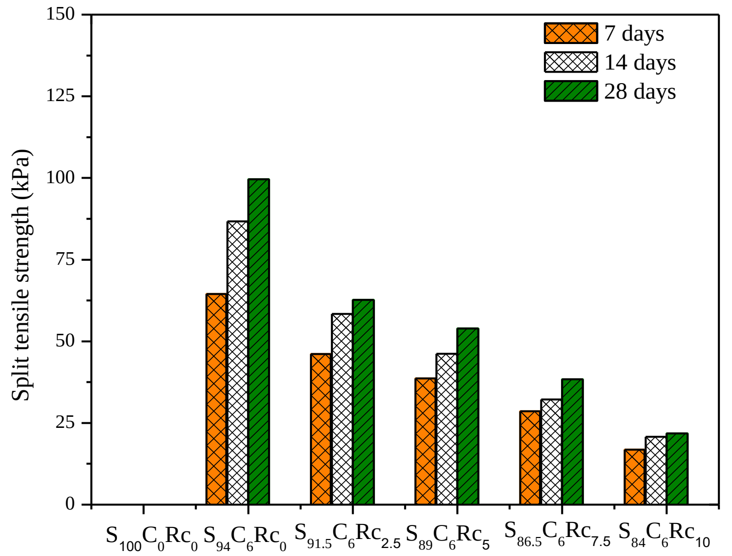


Fig. 5.34 Variation of split tensile strength of clayey soil mixed with 6% cement and rubber crumbles and cured for 7, 14, and 28 days (Soaked condition)

A study of Figs 5.31 and 5.34reveal an increase in the split tensile strength of clayey soil-cement-rubber crumbles mixtures with the increase in cement content and curing time. For example, the split tensile strength of 7 days cured specimen $S_{89}C_6Rc_5$ was 43.35 kPa, which increased to 57.79 kPa and 68.13 kPa with the increase in curing period from 14 and 28 days, respectively. The reason of increase in tensile strength has already been explained in section 5.3.6. Similar trend of increase in split tensile strength of clayey soil-cement-rubber crumbles mixtures with the increase in cement content and curing time was observed for soaked specimens as shown in Figs. 5.33 and 5.34.

A study of Figs. 5.31 and 5.32reveal a decrease in tensile strength with the increase in rubber crumbles content. For example, the split tensile strength of 28 days cured specimen $S_{94.5}C_3Rc_{2.5}$was 56.32 kPa, which decreased to 45.99 kPa, 31.66 kPa, and 19.49 kPa for specimen $S_{92}C_3Rc_5$, $S_{89.5}C_3Rc_{7.5}$, and $S_{87}C_3Rc_{10}$, respectively. Similarly, a value of tensile strength of 83.89 kPa for specimen $S_{91.5}C_6Rc_{2.5}$at 28 days of curing decreased to 68.13 kPa, 45.94 kPa, and 27.29 kPa with the increase in rubber crumbles content to 5%, 7.5% and 10%, respectively. The reason of decrease in split tensile strength has been discussed in detail during the discussion of unconfined compressive strength of the composite in section 5.3.6. Similar trend of decrease in split tensile strength of the clayey soil-cement-rubber crumbles mixtures with the increase in rubber crumbles was observed for soaked specimens as shown in Figs. 5.33 and 5.34. The reduction in split tensile strength of clayey soil-cement-rubber crumbles mixtures is observed due to immersion in water as shown in Figs. 5.31 to 5.34. For example, the split tensile strength of 28 days cured specimens $S_{94.5}C_3Rc_{2.5}$and $S_{91.5}C_6Rc_{2.5}$was 56.372 kPa and 85.7 kPa in unsoaked conditions, which reduced to 38.50 kPa and 62.67 kPa in soaked condition. This is may be possibly due to the intrusion of water in the matrix, which debilitated the bond by reducing cohesion and suction. The increment in water content may also weaken the interfacial mechanical interactions between rubber and clay-cement matrix, which ultimately reduces the capability of the matrix to bear tensile forces.

5.5 CALIFORNIA BEARING RATIO VALUE

The load-penetration curves of clayey soil-cement-rubber crumbles mixtures obtained from California Bearing Ratio tests for both unsoaked and soaked conditions are shown in Figs. 5.35 to 5.48.

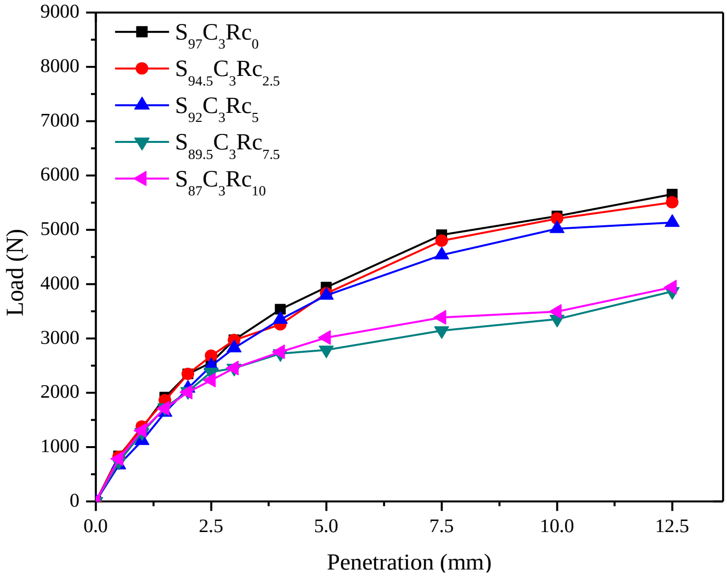


Fig. 5.35 Load- penetration curves of clayey soil mixed with 3% cement and rubber crumbles (Unsoaked condition)

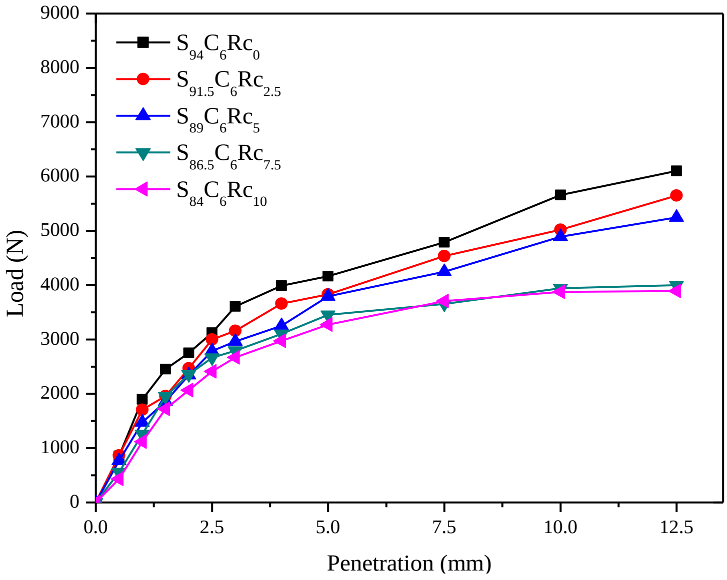


Fig. 5.36 Load- penetration curves of clayey soil mixed with 6% cement and rubber crumbles (Unsoaked condition)

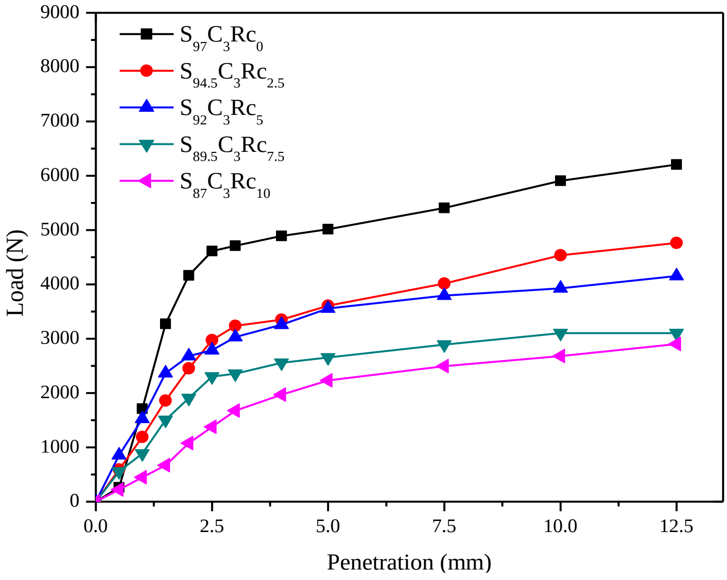


Fig. 5.37 Load- penetration curves of clayey soil mixed with 3% cement and rubber crumbles (Soaked condition)

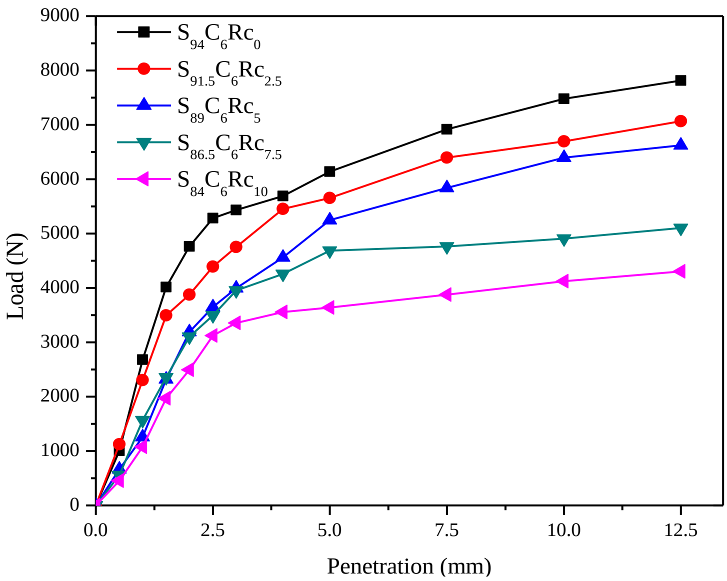


Fig. 5.38 Load- penetration curves of clayey soil mixed with 6% cement and rubber crumbles (Soaked condition)

Figs. 5.39 and 5.40 demonstrate the variation of California Bearing Ratio values of clayey soil-rubber crumbles mixture containing 3% and 6% cement of both unsoaked and soaked condition, respectively. The California Bearing Ratio value of clay in unsoaked and soaked condition is 10.59% and 8.69%, respectively (as shown in Fig. 4.28). When cement is introduced in the mixture, the CBR value of clayey soil for unsoaked and soaked condition increases significantly, this is an indication of the increase in strength and stiffness. For example, the unsoaked CBR values of the mixture $S_{97}C_3Rc_0$ and $S_{94}C_6Rc_0$ was19.19%, and 22.65% respectively, which is 1.81 and 2.13 times greater than clayey soil in unsoaked condition. The CBR values of cemented clay in soaked conditions are found much greater than unsoaked conditions. For example, the CBR value of mixture $S_{94}C_6Rc_0$ was 22.56% in unsoaked condition, which increased to 38.56% for the same mixture in soaked condition. These observations are in agreement with the results reported by the other researchers (Cabalar et al. (2014)). The increase in soaked CBR value of mixture may be attributed to the pozzolanic reaction between cement and clayey particles with lead to the formation of cementious products.

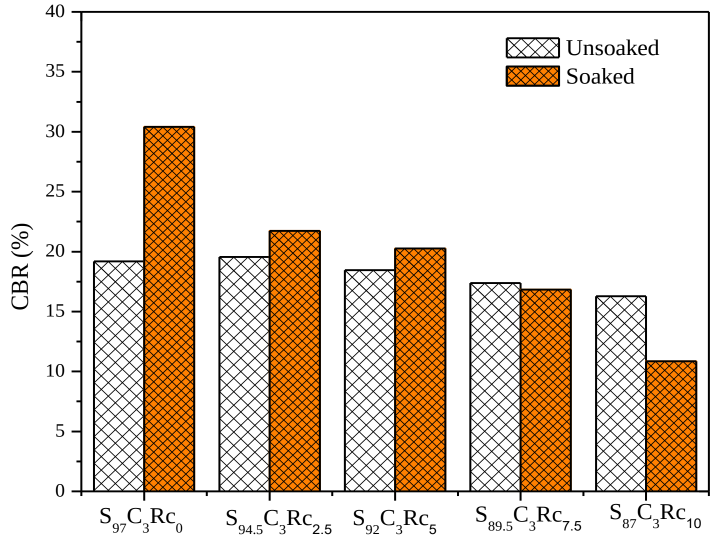


Fig. 5.39 Variation of California bearing ratio (%) of clayey soil mixed with 3% cement and rubber crumble

It is observed from Figs. 5.39 and 5.40 that as the rubber crumble content increases from 2.5% to 10% in cemented clay, the CBR value decreases. For example, the soaked CBR value of specimen $S_{97}C_3Rc_0$ decreases by 28.5%, 33.37%, 44.62%, and 64.28% with the inclusion of 2.5%, 5%, 7.5%, and 10% rubber crumbles content. Similarly, the reduction in soaked CBR value of $S_{94}C_6Rc_0$ is found 17.11%, 28.79%, 33.97%, and 40.98% with the addition of 2.5%, 5%, 7.5%, and 10% rubber crumbles, respectively. The decrease in CBR of cement stabilized clayey soil with increasing the rubber crumbles content may be attributed to higher compressibility of rubber particles than that of soil particles, which lead to lower the resistance against penetration. The soaked CBR values of cemented clay-rubber specimens are more than unsoaked specimens with few exceptions. For example, the CBR value of specimen $S_{87}C_3Rc_{10}$ was 15.3% in unsoaked condition, which decreased to 10.7% for soaked condition. The CBR values of $S_{89.5}C_3Rc_{7.5}$and $S_{87}C_3Rc_{10}$are found more in unsoaked condition rather than the soaked condition. This is an indication of governance of interaction between rubber-to-rubber particles rather than rubber to cemented clay particles. The behaviour of specimens is controlled by rubber particles. These results are in agreement with Cabalar et al., (2014) but found contrary to the results reported by Otoko and Pedro, (2014) and Hambirao and Rakaraddi, (2014). Hambirao and Rakaraddi (2014) reported increase in the CBR values of the cemented clay up to 5% inclusion of rubber content.

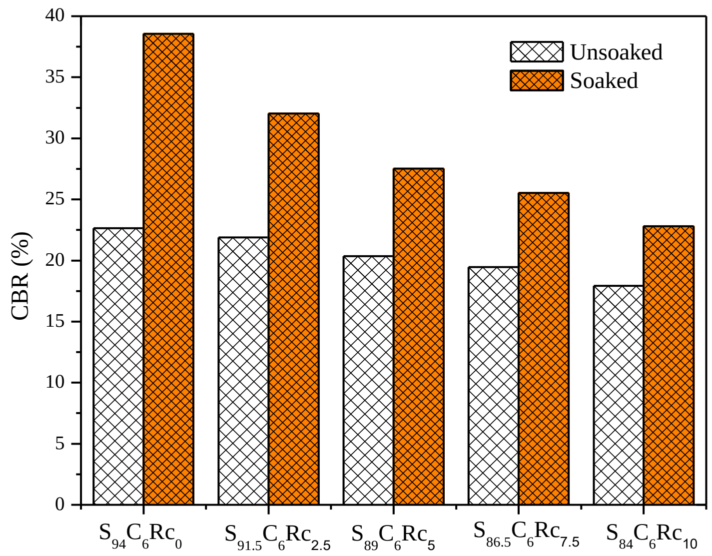


Fig. 5.40 Variation of California bearing ratio (%) of clayey soil mixed with 6% cement and rubber crumbles

5.6 ONE-DIMENSIONAL CONSOLIDATION

Figs. 5.41 and 5.42 show the vertical strain –log σ’ curves of clayey soil-rubber crumbles specimens containing 3% cement and 6% cement, respectively. For the purpose of comparison, compression characteristics of clayey soil-cement-rubber crumbles mixtures have been presented in terms of vertical strain rather than void ratio. The gradient of consolidation curve line of clayey soil changes due to the inclusion of rubber and cement. The curves become flat with very less compression as compared to the clayey soil up to a certain limit followed by sudden compression with the inclusion of cement in clayey soil, which can be attributed to the breakage of cementation bonds. When rubber crumbles are introduced in cemented clay, this sudden compression has been overcome which is due to compression taking ability of rubber crumbles.

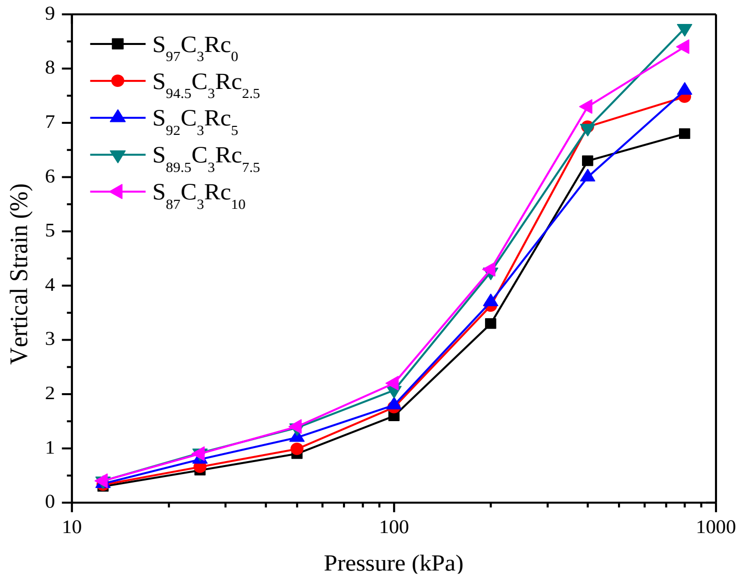


Fig. 5.41 Compression Curves of clayey soil mixed with 3% cement and rubber crumbles

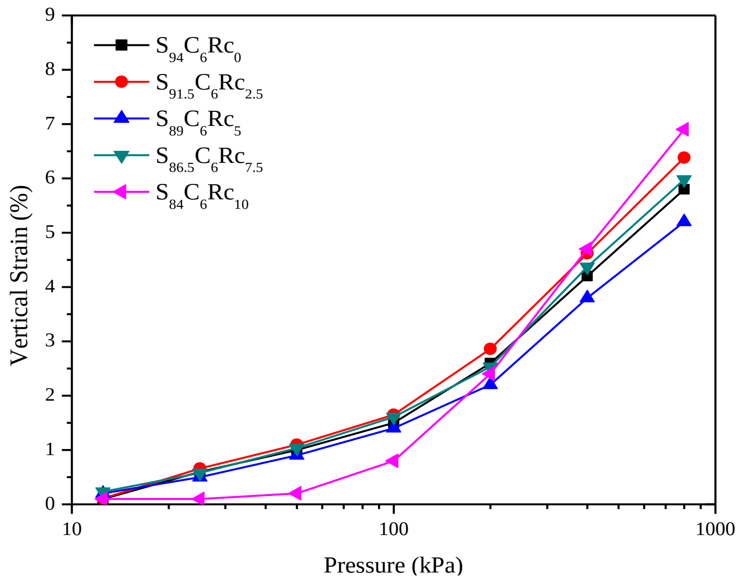


Fig. 5.42 Compression Curves of clayey soil mixed with 6% cement and rubber crumbles

The compression indices of the clayey soil-cement-rubber crumbles mixtures obtained from consolidation curves are summarised in Table 5.5. The C_C decreases dramatically with the increase in cement content and increases with the increase in rubber content. A high increase in compression index is observed at rubber content more than 5% in the clayey soil-cement- rubber crumbles mixtures containing 3% cement. These observations are similar to that reported by Ho et al., (2010). Similarly, at 6% cement mixtures, the compression index of clayey soil-cement- rubber crumbles mixtures increases with the increase in rubber crumbles content up to 5%, followed by higher increases in compression index values for rubber content greater than 5%. When more rubber crumbles are added, the specimens would turn into a granular material and become the dominating factor over cementation effect. The increase in C_C values could be attributed to the increased void ratio resulting from the addition of rubber crumbles to the cement-treated clayey soil and the compression of these voids resulted in higher C_C values.

Table 5.5 Results of consolidation tests on clayey soil mixed with cement and rubber crumbles

Cement content (%)	**Compression index (C_C)**				
	Rubber crumbles content (%)				
	0	**2.5**	**5**	**7.5**	**10**
3	0.349	0.351	0.365	0.381	0.410
6	0.192	0.207	0.231	0.256	0.276

5.7 SWELLING PRESSURE

The results of swelling pressure tests on various combinations of clayey soil-cement-rubber crumbles mixtures are shown in Fig. 5.43. The swelling pressure of clayey soil was 70.12 kPa (as shown in Fig. 4.33). It can be observed from Fig. 5.43 that the swelling pressure of clayey soil decreases steadily with the increase in cement and rubber crumbles content. With the addition of 3% and 6% cement, the swelling pressure of clayey soil decreases from 70.12 kPa to 45.33 kPa and 26.58 kPa, respectively. The reduction in swelling pressure of clayey soil with the addition of cement may be due to cementation reactions between clay and cement minerals in the presence of moisture. Three chemical reactions namely, cation exchange, flocculation-agglomeration and hydration reaction take place between moist clay and cement mixture. The cation exchange process promotes the flocculation-agglomeration phenomenon of clay particles due to the formation of net attractive force between clay particles and ultimately reduces the plastic behaviour and swelling potential. The hydration reaction of cement leads to the formation of cementitious compounds like, Calcium-Silicate-Hydrates (C-S-H) and Calcium-Aluminium-Hydrates(C-A-H), which harden with time and spur solidification and ultimately diminishes swelling potential of the clay.

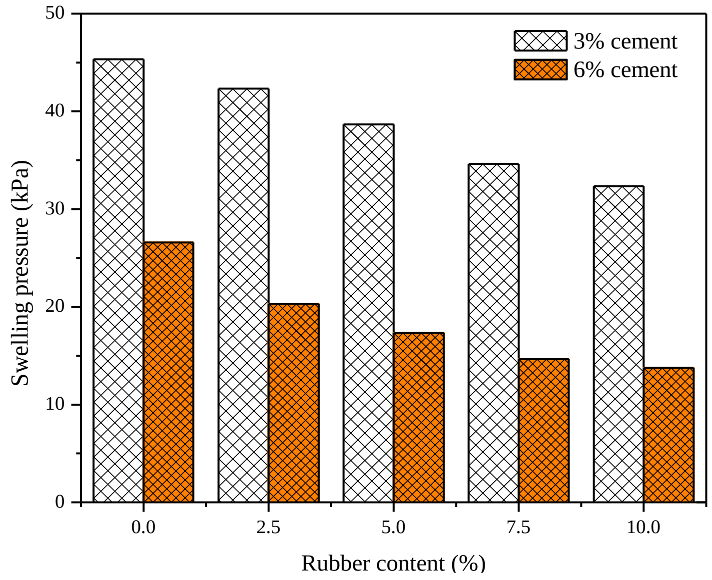


Fig. 5.43 Variation of swelling pressure of clayey soil mixed with cement and rubber crumbles

It is observed from Fig. 5.43 that addition of rubber crumbles causes the further reduction in swelling pressure of cement stabilized clayey soil. The swelling pressure of clayey soil stabilized with 3% cement decreases from 45. 33 kPa to 42.33 kPa, 38.66 kPa, 34.62 kPa and 32.33 kPa with the addition of 2.5%, 5%, 7.5%, and 10% rubber crumbles content, respectively. Similarly, the incorporation of 2.5%, 5%, 7.5%, and 10% rubber crumbles content lowers the swelling pressure of clayey soil containing 6% cement from 26.58 kPa to 20.33 kPa, 17.35 kPa, 14.66 kPa, and 13.76 kPa, respectively. The possible reason of this decrement in swelling pressure of cement stabilized clayey soil with the inclusion of rubber crumble is the creation of drainage paths for dissipation of pore pressures, substitution of swelling clay particles with non-swelling rubber crumbles particles and restraining of swelling pressures by the rubber crumbles.

5.8 DURABILITY BEHAVIOUR

The continuous wetting and drying impact the serviceability and performance of clayey soil-cement-rubber crumbles mixtures. The durability of composite depends upon the pore structure, tensile strength, inter-particle friction and cohesion of the materials. The test result of wet-dry durability in term of weight loss of 7, 28, 90, and 180 days cured specimens plotted against the number of cycles are shown in Figs. 5.44, 5.45, 5.46, and 5.47, respectively.

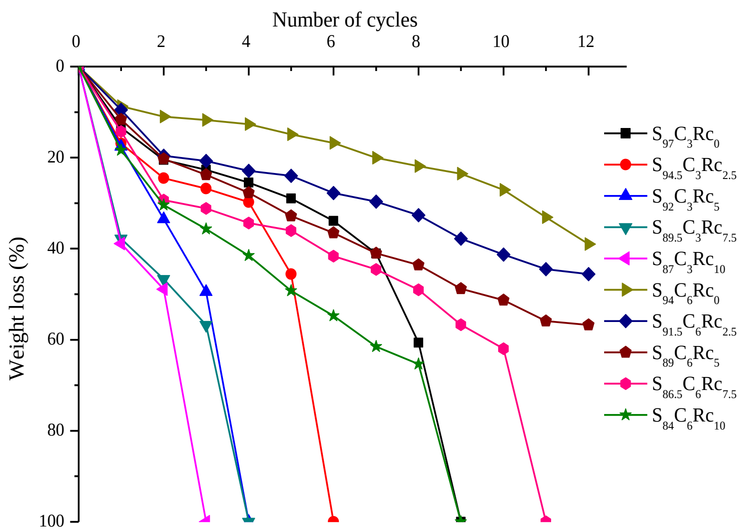


Fig. 5.44 Variation of weight loss- Number of cycles of clayey soil mixed with cement and rubber crumbles and cured for 7 days

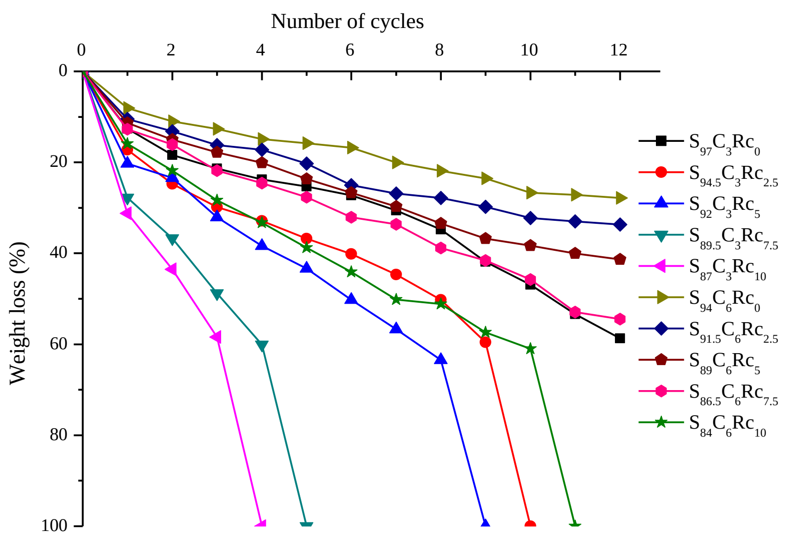


Fig. 5.45 Variation of weight loss- Number of cycles of clayey soil mixed with cement and rubber crumbles and cured for 28 days

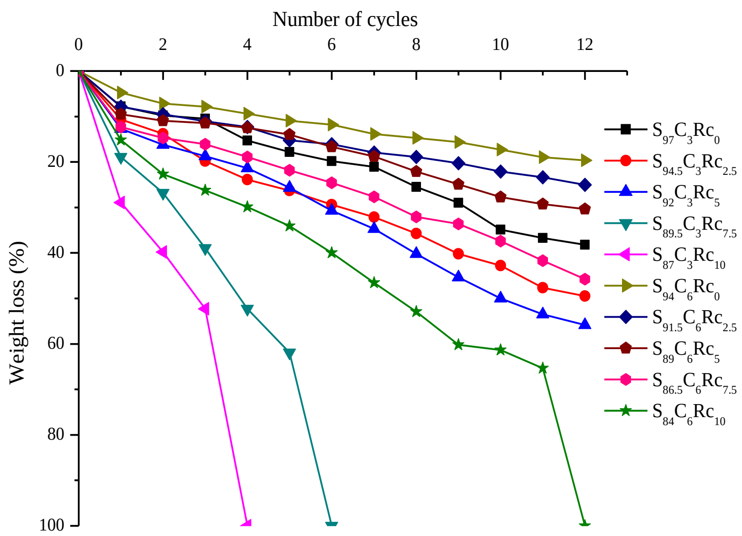


Fig. 5.46 Variation of weight loss- Number of cycles of clayey soil mixed with cement and rubber crumbles and cured for 90 days

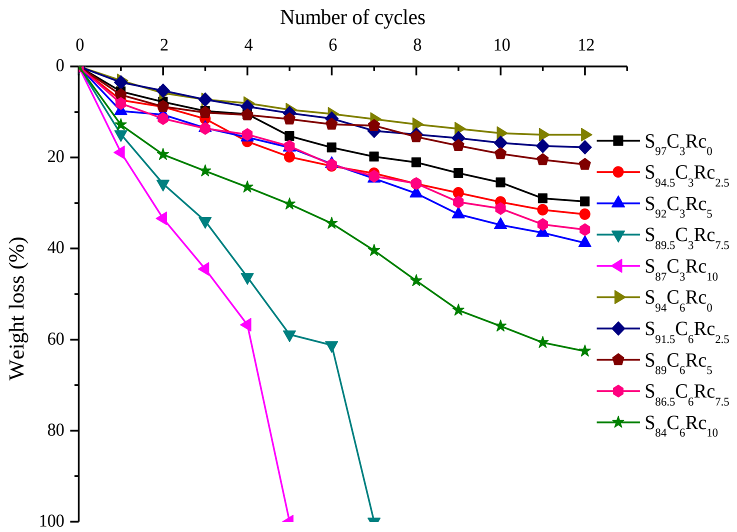


Fig. 5.47 Variation of weight loss- Number of cycles of clayey soil mixed with cement and rubber crumbles and cured for 180 days

7 days cured specimens of clay containing 3% cement and 2.5%-10.0% rubber crumbles content could not maintain the volumetric integrity and failed, along with specimen of clay containing 6% cement and 7.5% and 10% rubber crumbles before the completion of wet and dry process as illustrated in Fig. 5.44. While clayey soil specimens containing 6% cement and 2.5% and 5% rubber crumbles are successful to endure the complete 12 cycles of wetting and drying. On prolonging the curing period of specimens before subjected to wet and dry cycle,

all the specimens are able to survive the complete process of durability test (except for $S_{89.5}C_3Rc_{7.5}$, $S_{87}C_3Rc_{10}$and $S_{84}C_6Rc_{10}$specimens) as shown in Figs. 5.46 and 5.47.

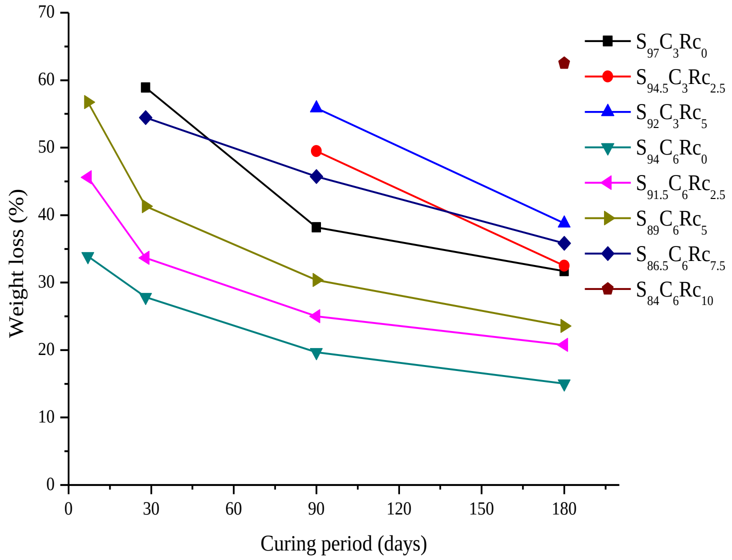


Fig. 5.48 Weight loss- curing period of the composites after completion of 12 wetting and drying cycles

Fig. 5.48 shows the variation of weight loss of specimens with the curing period after completion of 12 wetting and drying cycles. The weight loss of clayey soil mixed with cement decreases with the increase in cement content. For example, for 180 days cured specimen $S_{97}C_3Rc_0$, the weight loss was 31.68%, which decreased to 15.02% for specimen $S_{94}C_6Rc_0$. The weight loss of cemented clay incorporated with rubber crumbles increases consistently with the increase in rubber crumbles content. For example, the weight loss of 90 days cured specimen $S_{97}C_3Rc_0$was 38.20%, which increased to 49.47% and 55.84% for specimen $S_{94.5}C_3Rc_{2.5}$ and $S_{92}C_3Rc_5$, respectively. The disparate thermal elaboration between rubber and cemented clay during the dry cycle causes the deficiency in bond strength between rubber crumbles and cemented clay. Further, the abrasive action of wire brush, which was applied after the drying cycle, leads to void formation and increases the weight loss. Fig. 5.48shows that the weight loss of specimens containing 3% cement and varying percentages of rubber crumbles is higher than that of specimens containing 6% cement and varying percentages of rubber crumbles. For example, the weight loss of 49.47% and 55.84% for specimens $S_{94.5}C_3Rc_{2.5}$ and $S_{92}C_3Rc_5$ at 90 days of curing decreased to 25.0% and 30.38% for specimens $S_{91.5}C_6Rc_{2.5}$ and $S_{89}C_6Rc_5$, respectively. The weight loss of cemented clay specimens containing rubber crumbles decreases with the prolongation of curing period. For example, a weight loss of 45.6% for specimen $S_{91.5}C_6Rc_{2.5}$ cured for 7 days decreased to 33.67%, 25.0%, and 20.77%, respectively with the prolongation of curing period to 28, 90, and 180 days.

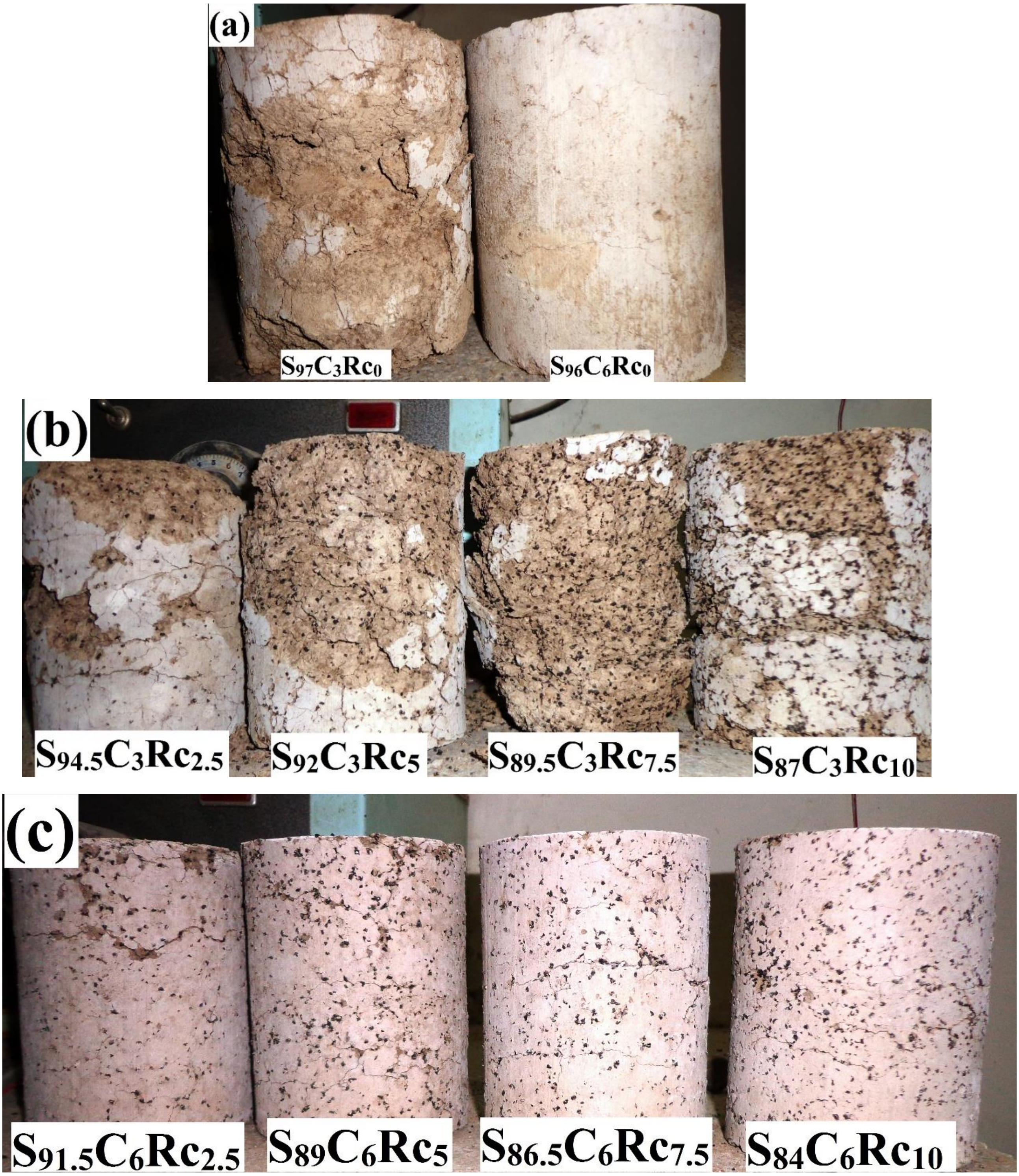


Fig. 5.49 Photograph of clayey soil mixed with cement and rubber crumbles cured for 180 days during the wetting and drying cycles

5.9 MINERALOGICAL AND MORPHOLOGICAL STUDIES

In the preceding sections 5.3 to 5.7, it has been seen that the content of cement and rubber crumbles affects the unconfined compressive strength, split tensile strength, California bearing ratio, compression index, swelling pressure and durability of clayey soil-cement-rubber crumbles mixtures. Keeping the above in view, XRD (X-ray diffraction) and SEM (scanning electron micrographs) analysis were carried out on the 28 days cured specimens of clayey soil-cement-rubber crumbles mixtures as per the procedure described in section 3.6.8 of chapter 3.

5.9.1 Mineralogical Studies

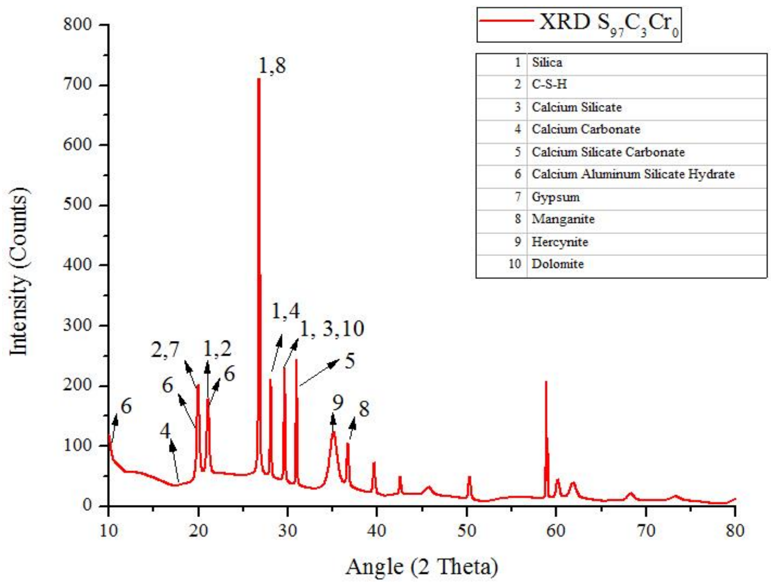


Fig. 5.50 X-Ray diffract gram of clayey soil mixed with 3% cement after 28 days of curing

Figs. 5.50 and 5.51 show the XRD pattern of $S_{97}C_3Rc_0$ and $S_{94}C_6Rc_0$after 28 days of curing. The crystalline phase present are identified from the peaks in pattern. With the inclusion of cement in clayey soil, changes in the mineralogical composition of mixes are observed. Several new peaks of calcium silicate hydrate (C-S-H), calcium aluminum silicate hydrate, calcium carbonate, calcium silicate, calcium silicate carbonate, etc. are visualized. These new peaks confirm the cementing products of hydration and pozzolanic reactions between clay and cement minerals. There is a reduction in peaks intensity of quartz from 715.59 to 691.08 respectively, for $S_{97}C_3Rc_0$ and $S_{94}C_6Rc_0$indicate the cementitious reactions taken place between the composite, which lead to the formation of hydration products. Kaolinite is completely exhausted which leads to the formation of pozzolanic reaction and additional cementitious products. Thus, it can be concluded that formation of C-S-H as evident from Figs. 5.50 and 5.51 attributes to the increase in unconfined compressive strength, split tensile strength, and California bearing ratio of clayey soil-cement-crumbles mixtures as compared to clay.

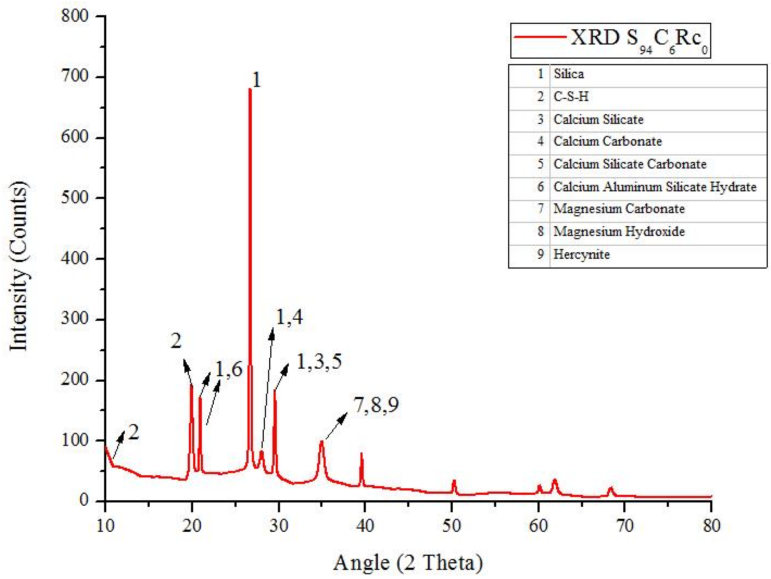


Fig. 5.51 X-Ray diffract gram of clayey soil mixed with 6% cement after 28 days of curing

5.9.2 Morphological Studies

The results of SEM of clayey soil-cement-rubber crumbles mixtures are shown Figs. 5.52(a) to 5.52(e). The dark portions in SEM images are assumed voids in matrix and fibrous crystals indicate C-S-H gel. Figs. 5.52(a) and 5.52(b) show the SEM images 28 days cured specimen of clayey soil stabilized with 3% cement. Figs. 5.52(c) and 5.52(d) show the SEM images 28 days cured specimen of clayey soil stabilized with 6% cement. Some micro-cavities and voids are observed in the specimen $S_{97}C_3Rc_0$ and $S_{96}C_6Rc_0$ at 100-x and 120-x magnification as shown in Figs. 5.52(a) and 5.52(c). As the content of cement increases, the hydration product increases as indicated in Figs. 5.50 and 5.51. The voids of compacted clayey soil (as shown in Fig. 4.37) has been filled by the cementitious gel formed by the hydration reaction indicated by fibrous crystals and enhances the inter-cluster bonding strength. The cementious gel formation could be clearly observed in Fig. 5.52(b) and 5.52(d) for specimen $S_{97}C_3Rc_0$ and $S_{96}C_6Rc_0$. The hydrated product like C-S-H and is most likely responsible for the increase in unconfined compressive strength, split tensile strength and California Bearing Ratio as observed in section 5.3 to 5.5 for specimen $S_{97}C_3Rc_0$ and $S_{96}C_6Rc_0$. At the interface of rubber crumbles and cement matrix, a gap can be visualized in Fig. 5.52(e) along with micro cracks in the $S_{92}C_3Rc_5$ specimen. The poor interaction between rubber crumbles and cemented clay leads to cracking, which ultimately results into reduction in unconfined compressive strength and split tensile strength of clayey soil-cement-rubber crumbles mixtures observed in section 5.6 and 5.7, respectively. These gaps are also responsible for reduction in soaked California Bearing Ratio values and swelling pressure of clayey-cement-rubber crumbles mixtures as were observed in section 5.6 and 5.7, respectively.

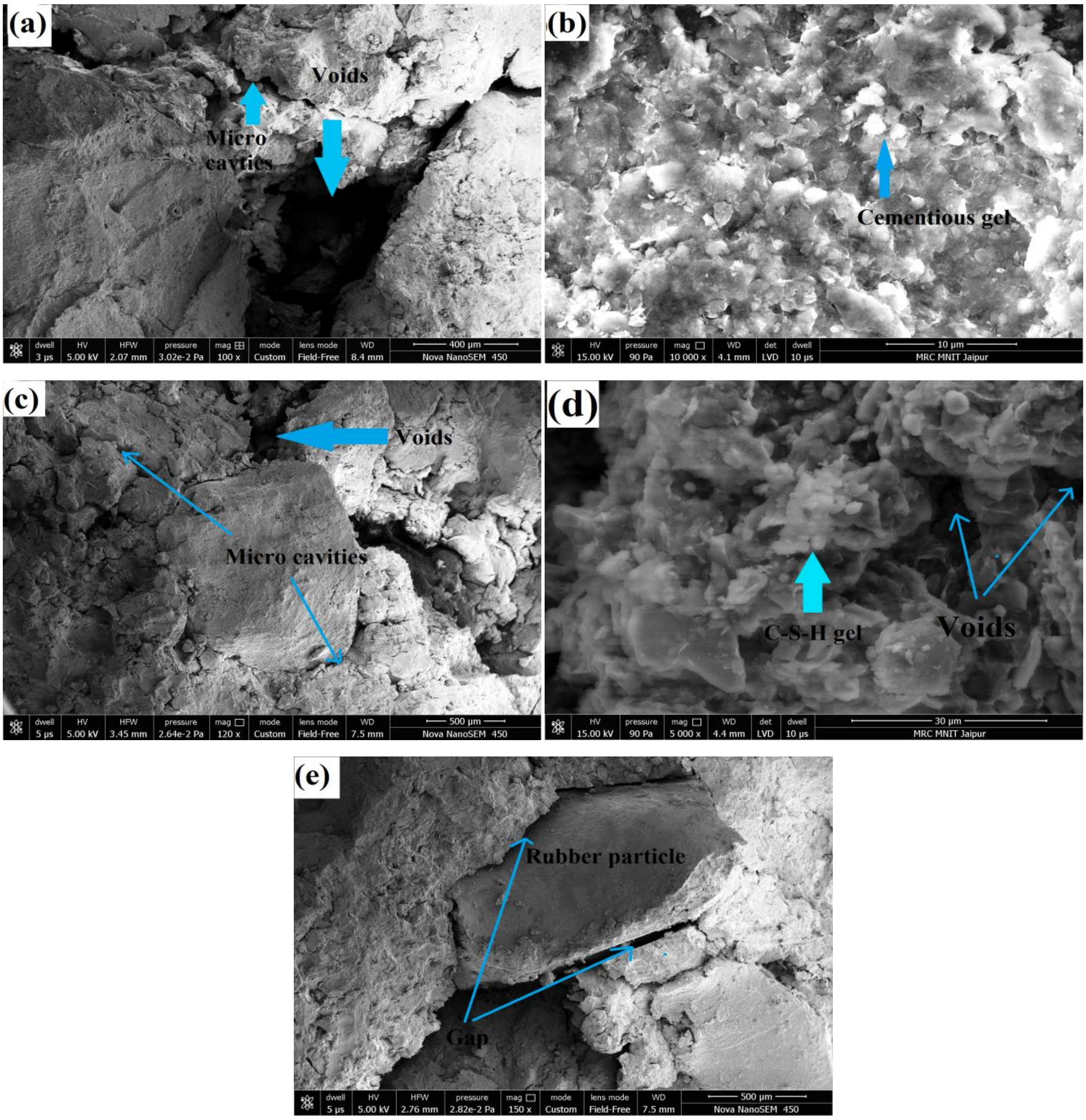


Fig. 5.52SEM Photograph of specimens cured for 28 days **(a)** $S_{97}C_3Rc_0$ (5KV, 100x, 400 µm), **(b)** $S_{97}C_3Rc_0$ (15KV, 10000x, 10 µm), **(c)** $S_{96}C_6Rc_0$ (5KV, 120x, 500 µm), **(d)** $S_{96}C_6Rc_0$ (15KV, 5000x, 30 µm), **(e)** $S_{92}C_3Rc_5$ (15KV, 150x, 500 µm).

5.10 STATISTICAL ANALYSIS

Multiple linear regression analysis (MLRA) is used to develop the best relationship between one continuous dependent variable and two or more dependent variables. In the study, Statistical software SPSS 12.0 was used to investigate the relationship between dependent variable and independent variables. A general model for formulating MLRA for a given observation is given below:

$$\mu_y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots\ldots\ldots\ldots + \beta_p x_p \quad (5.1)$$

Where

μ_y is dependent variable, x_i indicates independent variables and β_i depicts predicted parameters, respectively.

Based on the modified proctor, unconfined compressive strength, split tensile strength, California Bearing Ratio, one-dimensional consolidation, and swelling pressure test results, multiple regression models were developed to predict the maximum dry unit weight, optimum moisture content, unconfined compressive strength, split tensile strength, California Bearing Ratio value, compression index, and swelling pressure of the clayey soil-cement-rubber crumbles mixtures. The equation for predicating the values of maximum dry unit weight, optimum moisture content, unconfined compressive strength, split tensile strength, California Bearing Ratio value, compression index, and swelling pressure of clayey soil-cement-rubber crumbles mixtures are given below:

Maximum dry unit weight (predicted) = 16.491 - 0.067*C - 0.164*Rc (5.2)

Optimum moisture content (predicted) = 20.808 + 0.115*C - 0.277*Rc (5.3)

Unsoaked UCS (Predicted) = 48.217 + 47.717*C - 15.99*Rc+ 2.099*CT (5.4)

Soaked UCS (Predicted) = -33.851 + 46.068*C - 21.780*Rc + 2.338*CT (5.5)

Unsoaked STS (Predicted) = 44.001 + 6.779*C - 7.046*Rc + 0.783*CT (5.6)

Soaked STS (Predicted) = 12.986 + 8.946*C - 6.052*R c + 0.691*CT (5.7)

Unsoaked CBR value (Predicted) = 13.948 + 1.471*C - 0.32*Rc (5.8)

Soaked CBR value (Predicted) = 13.971 + 3.642*C - 1.196*Rc (5.9)

Compression index (Predicted) = 0.474- 0.047*C + 0.007*Rc (5.10)

Swelling pressure (predicated) = 67.085 - 6.655*C - 1.713*Rc (5.11)

Where

C = Content of cement (%)
Rc = Content of rubber crumbles (%)
CT = Curing time, days

The values of the relevant statistical coefficients like coefficient of multiple determination (R_2), adjusted coefficient of multiple determination ($R^2_{adjusted}$), standard error of the estimate (SE), and confidence level (CL) of maximum dry unit weight, optimum moisture content, unconfined compressive strength, split tensile strength, California Bearing Ratio value, compression index, and swelling pressure have been given in Table 5.6. The scatter plot of predicated and observed maximum dry unit weight, optimum moisture content, unconfined compressive strength, split tensile strength, California Bearing Ratio value, compression index, and swelling pressure of clayey soil mixed with cement and rubber crumbles are shown in Appendix (Fig. A33 to A39).

Fig. 5.6 Statistical coefficients of the tests

Attributes	**Statistical coefficients**			
	R^2	**$R^2_{adjusted}$**	**SE**	**CL (%)**
Maximum dry unit weight	0.989	0.986	0.0737	95
Optimum moisture content	0.958	0.946	0.2488	95
Unsoaked UCS	0.956	0.950	21.547	95
Soaked UCS	0.916	0.903	25.825	95
Unsoaked STS	0.863	0.847	11.875	95
Soaked STS	0.927	0.916	6.101	95
Unsoaked CBR	0.847	0.822	1.789	95
Soaked CBR	0.933	0.922	2.950	95
C_C	0.990	0.987	0.018	95
Swelling pressure	0.983	0.980	2.551	95

The coefficient of determination (R^2) of equations (5.2) to (5.11) is closure to unity. Hence the developed equations for predicting the maximum dry unit weight, optimum moisture content, unconfined compressive strength, split tensile strength, California Bearing Ratio value, compression index, and swelling pressure of clayey soil-cement-rubber crumbles mixture could be considered satisfactory.

Despite the simplicity of model, the author suggests that the model is valid within the range of cement and rubber crumbles content and material tested. Beyond this range of values, the models may be checked with experimental results.

5.11 CONCLUSIONS

Based on the test results presented in this chapter, the following broad conclusions may be drawn.

5.11.1 Compaction studies

From the compaction studies, it is concluded that both maximum dry density and optimum moisture content of the clayey soil-cement-rubber crumbles mixtures decreases as the content of rubber crumbles increases.

5.11.2 Compression and Tension Behaviour

From the unconfined compression and tension behaviour, the following conclusions are drawn:

- The inclusion of cement in clayey soil increases unconfined compressive strength and split tensile strength remarkably but lowers the axial and diametral deformation corresponding to peak load. A sudden drop in the post peak load is also observed, which indicates the brittle behaviour of cemented clay.
- The inclusion of rubber crumbles in cemented clay caused a decrease in unconfined compressive strength and split tensile strength. The axial and diametral deformation corresponding to peak load increases with the inclusion of rubber crumbles up to 5%; further incorporation of rubber crumbles decreases the axial and diametral deformation.
- In compression, the absolute toughness of cement-stabilized clayey soil is more than rubberized cement-stabilized clay. It increases with the inclusion of rubber crumbles up to 5%, there after it decreases for unsoaked condition. The absolute toughness of the clayey soil-cement-rubber crumbles mixtures under compression for soaked condition decreases continuously with the increase in rubber content.

The absolute toughness values of cement stabilized clayey soil incorporated with rubber crumbles increases with the increase in cement content.

- The inclusion of rubber crumbles up to 5% increases the toughness index of cement-stabilized clay. It is observed that the TI values of cement stabilized clayey soil incorporated with rubber crumbles decreases as the content of cement increases. The incorporation of rubber crumbles in cemented clay decreases the stiffness and loss of post peak strength of the composite. The brittle behavior of cement-stabilized clay under compressive load is somewhat overcome with the inclusion of rubber crumbles by lowering the rate of loss of post-peak strength. The effect of rubber crumbles in improving the post-peak response of cemented clayey soil containing rubber crumbles under tensile load is ineffective.
- The values of absolute toughness of clayey soil-cement-rubber crumbles mixtures in compression are more than tension for almost all the mixes. Similarly, the values of toughness index of clayey soil-cement-rubber crumbles mixtures in compression are more than tension. The values of toughness index of clayey soil-cement-rubber crumbles mixtures under tensile load are very less as compared to the compression.
- The compressive axial load, tensile load, compressive axial deformation, diametral deformation, unconfined compressive strength, tensile strength, absolute toughness and toughness index in compression and tension of the clayey soil-cement-rubber crumbles increased with the increase in curing period.
- The catastrophic failure with vertical crack in specimen of cement stabilized clayey soil is observed. The inclusion of rubber crumbles promotes the formation of multiple crack/staggered cracks and consequently prevents complete brittle failure of the composite in compression. The small fissure in specimens of clayey soil-cement-rubber crumbles under tension may possibly lead to marginally improvement in the post-peak strength under tensile loads.
- Due to soaking, a significant loss in the unconfined compressive strength and split tensile strength is observed.

5.11.3 California Bearing Ratio value

From the California Bearing Ratio (CBR) studies, it is concluded that the CBR values of soaked specimens of cemented clay are more than unsoaked specimens. The CBR values of clayey soil-cement-rubber crumbles mixtures decrease as the rubber crumbles content increases.

5.11.4 One-dimensional consolidation

From the One-dimensional consolidation studies, it is concluded that the compression index values of cemented clay-rubber crumbles composite increases with the increase in rubber content, but found lower than the clay. The optimal dose of rubber crumbles in the composite should be restricted to 5%, after that, higher increase in C_C values is observed at lower cement content.

5.11.5 Swelling pressure

From the Swelling pressure studies, it is concluded that the swelling pressure of clayey soil-cement-rubber crumbles mixtures decreases as the content of rubber crumbles and cement increases.

5.11.6 Durability Behaviour

From the durability behaviour, the following conclusions are drawn:

- The weight loss of clayey soil specimen mixed with cement can be decreased with the increase in content of cement.
- A decrease in the weight loss of clayey soil-cement-rubber crumbles mixtures was observed with the increase in curing period.
- The weight loss of clayey soil-cement-rubber crumbles mixtures increased with the increase in rubber crumbles content.

5.11.7 Morphological studies

From the mineralogical and morphology studies, the following conclusions are drawn:

- Calcium silicate hydrate (C-S-H), calcium aluminium silicate hydrate, calcium carbonate, calcium silicate, calcium silicate carbonate etc. minerals are found in the cement stabilized clayey soil specimens.
- The formation of cementation products such as C-S-H attribute to the increase in strength of cement stabilized clayey soil specimens without/with rubber crumbles.
- From the SEM images, the C-S-H gel formation is clearly seen in cemented clay-rubber mixture, which is the main governing force in the composite.
- The presence of gap between the rubber crumble and cemented clay is an indication of weak interfaces resulting into strength reduction of the composite.

5.11.8Statistical analysis

The predicated values of maximum dry unit weight, optimum moisture content, unconfined compressive strength, split tensile strength, California Bearing Ratio value, compression index, and swelling pressureof clayey soil-cement-rubber crumbles mixtures are closely matching with the observed values.

CHAPTER 6

EFFECT OF WASTE RUBBER FIBRES ON THE GEOTECHNICAL PROPERTIES OF CLAYEY SOILSTABILIZED WITH CEMENT

6.1 GENERAL

This chapter explores the effect of addition of rubber fibres and cement content on geotechnical properties of clayey soil. The tests namely, modified proctor compaction, unconfined compressive strength, split tensile strength, California Bearing Ratio, one-dimensional consolidation, swelling pressure, and durability, along with the scanning electron microscopy were conducted on clayey soil-cement-rubber fibres mixtures to ascertain suitability of rubber fibres with cement stabilized clay. It may be recalled that the cement content of 3% and 6% and rubber fibres content of 0%, 2.5%, 5%, 7.5%, and 10% by weight of soil were chosen. Mixes were represented by three capital alphabets, and each alphabet was followed by a numeric value in subscript. The numeric value in subscript indicates the percentage of clay, cement and rubber fibres in the mix. The alphabets 'S', 'C', and 'Rf' represented the clayey soil, cement, and rubber fibres, respectively.

6.2 COMPACTION STUDIES

The maximum dry unit weight and optimum moisture content of clayey soil-cement-rubber fibres were determined by modified proctor tests. The compaction curves of different clayey soil-rubber fibres mixture containing 3% and 6% cement are shown in Figs. 6.1 and 6.2, respectively.

The variation of maximum dry unit weight and optimum moisture content of clayey soil-rubber fibres mixtures containing 3% and 6% cement are shown in Figs. 6.3 and 6.4, respectively. The effect of inclusion of cement on maximum dry unit weight and optimum moisture content has already been discussed in Chapter 5, Section 5.2. The combined effect of rubber fibres and cement on compaction parameters of clayey soil is shown in Figs. 6.3 and 6.4. It can be inferred from graphs that the inclusion of rubber fibres in cemented clay further decreases the maximum dry unit weight of the mixtures. For example, the maximum dry unit weight of combination $S_{94.5}C_3Rf_{2.5}$ was 15.8 kN/m^3, which decreased to 14.8 kN/m^3

for mixture $S_{87}C_3Rf_{10}$.The decrease in maximum dry unit weight of clayey soil-cement-rubber fibres mixtures may be due to the elastic response of rubber fibres, which leads to decrease in compaction efficiency, and the low specific gravity of rubber fibres. The specific gravity of rubber fibres is 1.07, which is quite lower than the specific gravity of natural soil used in this investigation.

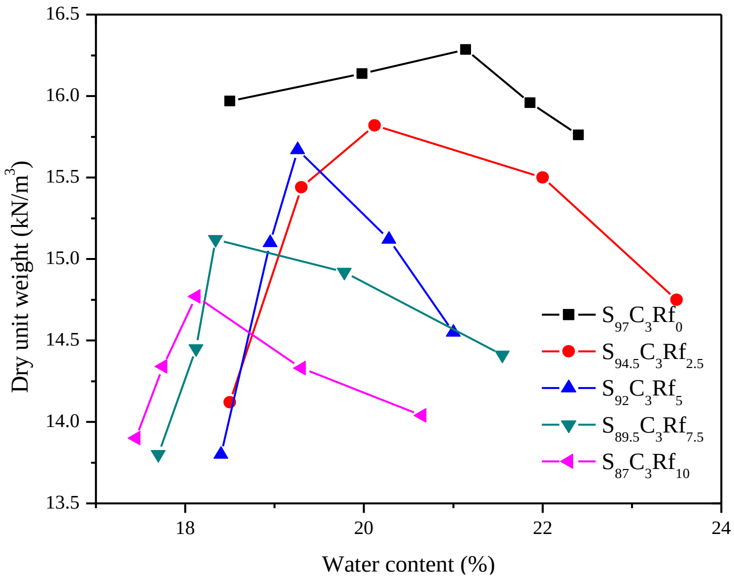


Fig. 6.1 Compaction curves of the clayey soil mixed with 3% cement and rubber fibres

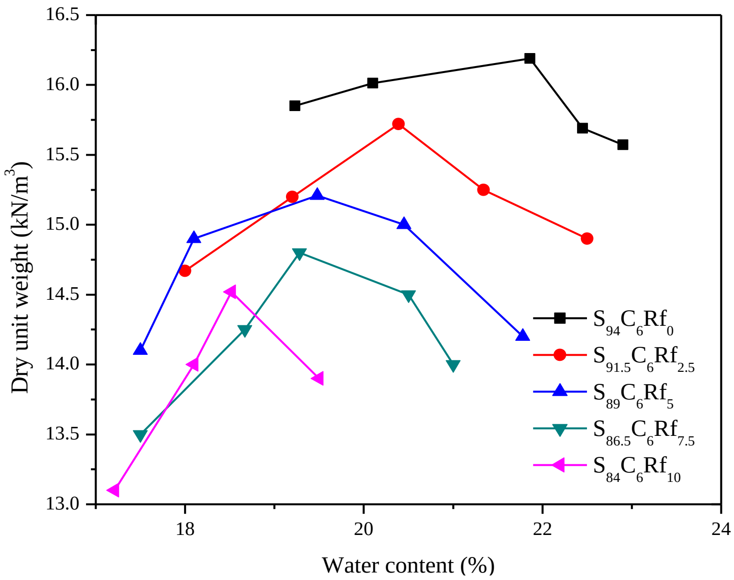


Fig. 6.2 Compaction curves of the clayey soil mixed with 6% cement and rubber fibres

Similarly, the optimum moisture content of combinations decreases with the increase in rubber fibres content. For example, the optimum moisture content of combination $S_{91.5}C_6Rf_{2.5}$

was 20.3%, which decreased to 18.5% for mixture $S_{84}C_6Rf_{10}$. The decrement in optimum moisture content may be due to the lower water absorption capacity of rubber fibres (Kalkan, 2013;Signes et al., 2016).This trend of maximum dry unit weight and optimum moisture content reduction is consistent with the results reported by other investigators (Kalkan, 2013;Srivastava et al., 2014; Cabalar et al., 2014;Signes et al., 2016)

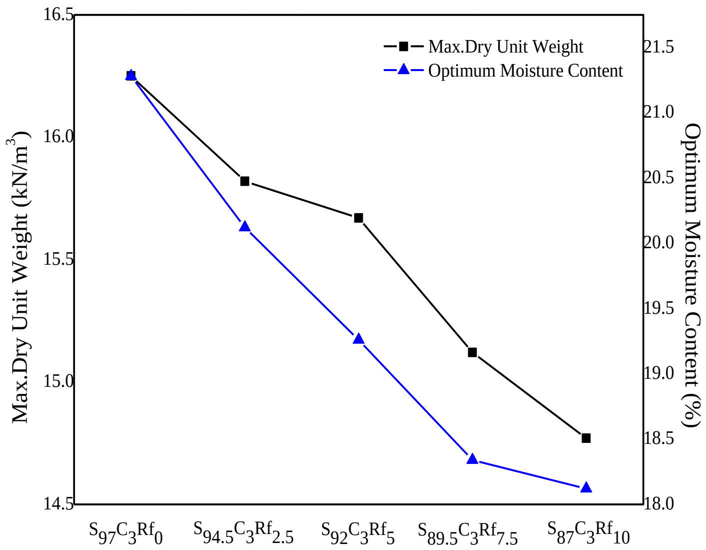


Fig.6.3 Variation of maximum dry unit weight and optimum moisture content of clayey soil-rubber fibres mixtures containing 3% cement

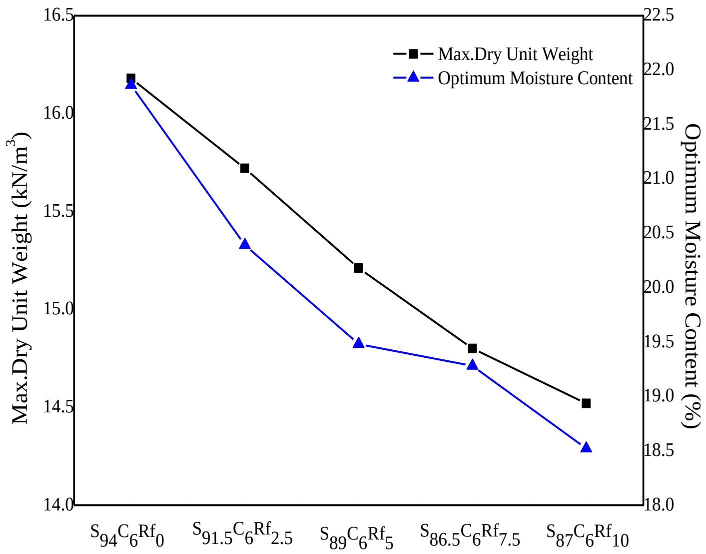


Fig.6.4 Variation of maximum dry unit weight and optimum moisture content of clayey soil-rubber fibres mixtures containing 6% cement

6.3 UNCONFINED COMPRESSION BEHAVIOUR

6.3.1 Axial load - Deformation response

Figs. 6.5 and 6.6 present the axial load-deformation response of 28 days cured clayey soil specimens incorporated with 2.5%, 5%, 7.5%, and 10% rubber fibres and 3% and 6% cement (unsoaked condition). The axial load-deformation curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber fibres and cured in humidity controlled room for 28 days followed by immersion in water for 24 hours are shown in Figs. 6.5 and 6.6 (soaked condition). The curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber fibres and cured for 7 and 14 days for both unsoaked and soaked condition are shown in Appendix (Figs. A33 to A40). The effect of inclusion of rubber fibres on axial load-deformation behaviour of clayey soil has already been discussed in section 4.3.1 of chapter 4.

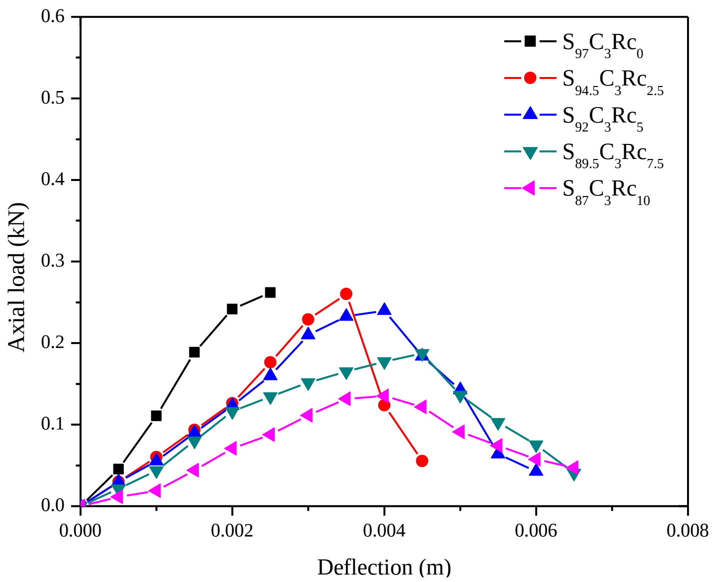


Fig. 6.5 Axial load- deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 28 days (Unsoaked condition)

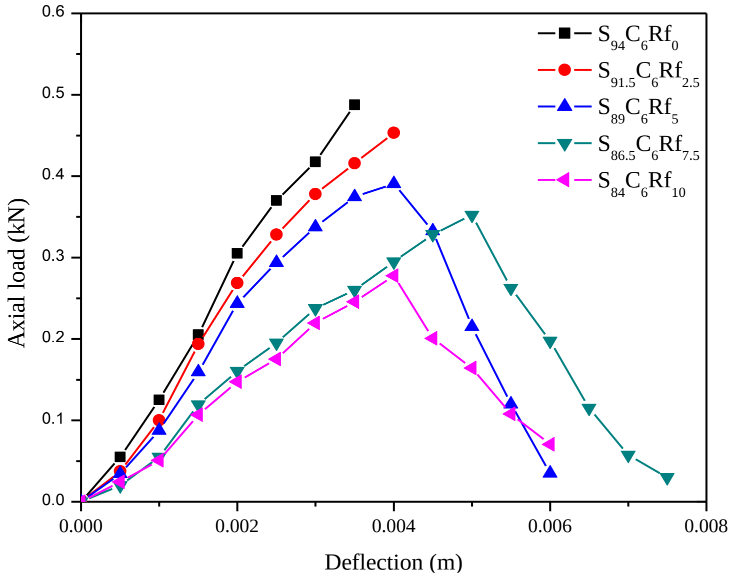


Fig. 6.6 Axial load- deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 28 days (Unsoaked condition)

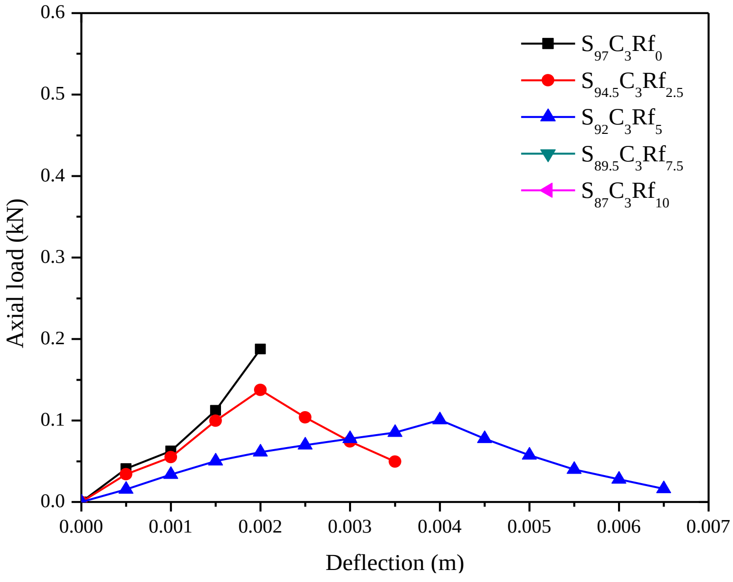


Fig. 6.7 Axial load- deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 28 days (Soaked condition)

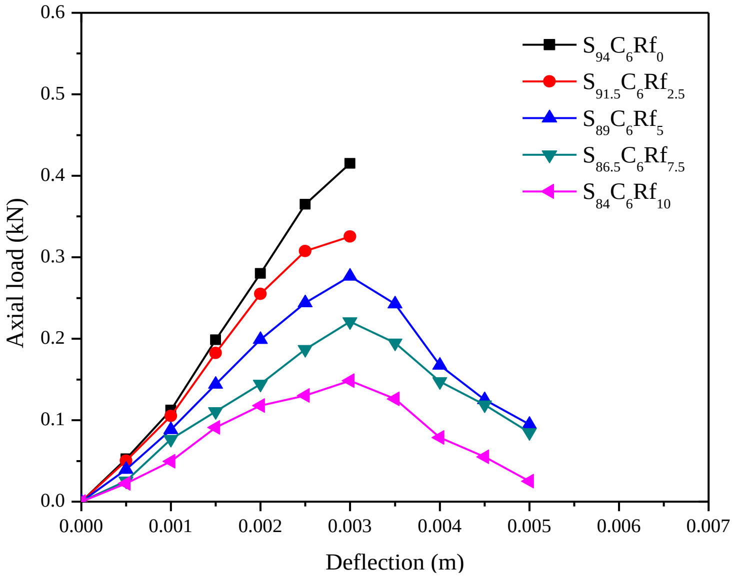


Fig. 6.8 Axial load- deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 28 days (Soaked condition)

The effect of inclusion of cement on axial load-deformation behaviour of clayey soil specimens cured for 7,14, and 28 days has already been discussed in chapter 5, section 5.3.1 for both unsoaked and soaked conditions.

The combined effect of both cement and rubber fibres inclusion on load-deformation response of clayey soil cured for 28 days is shown in Figs. 6.5 and 6.6 for unsoaked condition. It can be seen from Figs. 6.5 and 6.6 that the peak axial load of cemented clayey soil decreases with the increase in rubber fibre content. For example, the peak axial load of 28 days cured $S_{94.5}C_3Rf_{2.5}$specimen was 0.261 kN, which reduced to 0.239 kN, 0.187 kN, and 0.135 kN for specimens $S_{92}C_3Rf_5$, $S_{89.5}C_3Rf_{7.5}$, and $S_{87}C_3Rf_{10}$, respectively. Reduction in the peak stress may be due to (i)lesser stiffness of rubber fibres as compared to the cemented clay; (ii) difficulties in the packing of lightweight rubber fibres at high rubber content; (iii) decrease in friction and bonding between cemented clay and rubber particles (Kim and Kang, 2013)..The SEM image of rubber fibre reported in chapter 3, section 3.2.3 shows micro cracks on the surface, which could weaken the interfacial mechanical interaction between rubber fibres and cemented clay particles.

The inclusion of rubber fibres increases the deformation at failure of cemented clayey soil as indicated in Figs. 6.5 to 6.8. For example, for unsoaked specimen $S_{97}C_3Rf_0$, the deformation at failure was 0.0025 m, which increased to 0.004 m for specimen $S_{92}C_3Rf_5$.A close examination of Figs. 6.5 to 6.8 shows an increase in deformation at failure with the increase in rubber fibres content up to 7.5%. For example, for unsoaked specimen $S_{94}C_6Rf_0$, the deformation at failure was 0.0035 m, which increased to 0.005m for specimen $S_{86.5}C_6Rf_{7.5}$. However, the soaked specimens of clayey soil-rubber fibres mixtures stabilized with 6% cement shows same value of deformation at failure as indicated in Fig. 6.8.

The study of Figs. 6.5 to 6.8 and Appendix (Figs. A33 to A40) reveal that the peak axial load of clayey soil-cement-rubber fibres specimen's increases with the increase in curing period. For example, the peak axial load of 7 days cured specimen $S_{89}C_6Rf_5$ in unsoaked condition was 0.355 kN, which increased to 0.391 kN and 0.410 kN after 14 and 28 days of curing respectively. Further study ofFigs.6.5 to 6.8 and Appendix (Figs. A33 to A40) reveal an increase in deformation at failure with the increase in curing period. For example, the deformation at failure of 7 day unsoaked specimen $S_{86.5}C_6Rf_{7.5}$ was 0.004 m, which increased to 0.005 m with the change in curing period to 14 and 28 days, respectively. Similar trend of increase in deformation with the increase in curing period was observed for soaked specimens as well. For example, for soaked specimen$S_{89}C_6Rf_5$ (7 days cured), the deformation was 0.0025 m, which increased to 0.003 m after curing period of 14 and 28 days.

Figs. 6.7 and 6.8 show the similar trend of reduction in peak axial load for soaked specimens of clayey soil-cement-rubber fibres with the increase in rubber fibres content. For example, the peak axial load of soaked specimen $S_{91.5}C_6Rf_{2.5}$was 0.325 kN, which reduced to 0.276 kN, 0.221 kN, and 0.148 kN for specimens $S_{89}C_6Rf_5$, $S_{86.5}C_6Rf_{7.5}$, and $S_{84}C_6Rf_{10}$, respectively. Comparison of Figs. 6.5 and 6.6, and Fig. 6.7 and 6.8 shows that the peak axial load of clayey soil-cement-rubber fibres specimens decreases when subjected to curing under water for 24 hours before the test. For example, the peak load of unsoaked specimens $S_{92}C_3Rf_5$ and $S_{89}C_6Rf_5$ was 0.239 kN and 0.415 kN, which reduced 0.104 kN, and 0.276 kN after immersion. The reason of reduction in peak axial load of the specimens due to immersion has already been mentioned in chapter 5, section 5.3.1. Similar to the specimens $S_{89.5}C_3Rc_{7.5}$ and $S_{87}C_3Rc_{10}$, the specimens $S_{89.5}C_3Rf_{7.5}$ and $S_{87}C_3Rf_{10}$ disintegrates after immersed in water as shown in Fig. 6.9.

Fig. 6.9 Disintegration of specimens after being immersed in water

It is observed that addition of rubber fibres lowers the rate of post peak load reduction and change the brittle behaviour of cemented soil with a sudden drop after attaining peak (as shown in Figs. 6.5 to 6.8 to ductile with post peak failure resistance. Similar to the specimen $S_{91.5}C_6Rc_{2.5}$, no residual strength of specimen$S_{91.5}C_6Rf_{2.5}$wasobserved as indicated in Fig. 6.8, which is probably due to higher cementation effect, which offsets the ductility induced in mixture by rubber fibres. The smooth reduction of post-peak load may be due to (i) the development of elastic reaction in rubber fibres in compression; (ii) confining effect induced by rubber fibres, which restrains cracking; (ii) shear strength and tensile strength mobilization along the failure surface. Similar trend was observed for the soaked specimens as well shown in Figs. 6.7 and 6.8.

6.3.2 Absolute toughness in compression

The area under axial load-deformation curve up to failure as shown in Fig. 4.7 of chapter 4, is termed as the absolute toughness or energy absorption of mix. The results of absolute toughness of clayey soil mixed with 3% and 6% cement and 0%, 2.5%, 5%, 7.5%, and 10% rubber fibres, and cured at 7, 14, and 28 days are shown in Table 6.1 for both unsoaked and soaked conditions.

The effect of cement on absolute toughness of clayey soil has already been discussed in section 5.3.2 of chapter 5. It is observed from Table 6.1 that the absolute toughness of cemented clay increases with the increase in rubber content upto 7.5%. For example, from Table 6.1, the absolute toughness of 28 days cured specimen $S_{91.5}C_6Rf_{2.5}$ and $S_{89}C_6Rf_5$ was

0.000846 kN.m and 0.000863, which increased to a value of 0.000923 kN.m for specimen $S_{86.5}C_6Rf_{7.5}$.

Further incorporation of rubber fibres in cement stabilized clayey soil decreases, the absolute toughness. Table 6.1 further shows an increase in absolute toughness of the clayey soil-cement-rubber fibres mixtures with the increase in curing period. For example, for specimen $S_{86.5}C_6Rf_{7.5}$, a value of absolute toughness of 0.000689 kN.m at 7 days of curing, which increased to 0.000816 kN.m and 0.000923 kN.m with the increase in curing period to 14 and 28 days, respectively. Similar trend of increase in the absolute toughness of soaked clayey soil-cement-rubber fibres specimens were observed with the increase in cement content and curing period as evident in Table 6.1. Whereas, a continuous reduction in absolute toughness of soaked clayey soil-cement-rubber fibres specimens were observed with the increase in rubber fibres content. For example, the 28 days' absolute toughness of soaked specimen $S_{91.5}C_6Rf_{2.5}$ was 0.0000516 kN.m, which decreased to 0.000426 kN.m, 0.000327 kN.m, and 0.000242 kN.m for specimen$S_{89}C_6Rf_5$, $S_{86.5}C_6Rf_{7.5}$, and $S_{84}C_6Rf_{10}$, respectively.

Table 6.1 Absolute toughness of clayey soil mixed with cement and rubber fibres

Cement Content (%)	Curing period (days)	Absolute toughness (kN.m x 10^{-4})									
		Unsoaked condition					Soaked condition				
		Rubber fibres content (%)					Rubber fibres content (%)				
		0	**2.5**	**5**	**7.5**	**10**	**0**	**2.5**	**5**	**7.5**	**10**
3	7	1.872	1.944	3.534	3.829	1.988	0.418	0.843	NA	NA	NA
	14	2.158	3.231	3.843	3.925	2.171	1.118	1.025	1.007	NA	NA
	28	3.586	3.706	5.015	5.104	2.716	1.456	1.286	2.216	NA	NA
6	7	7.886	6.336	6.781	6.899	3.408	3.711	2.837	2.486	1.917	1.175
	14	8.656	7.900	8.453	8.816	5.331	4.387	4.472	3.818	2.999	1.953
	28	9.511	8.467	8.630	9.234	5.543	5.874	5.163	4.266	3.277	2.426

***** NA- Not applicable due to disintegration of specimen

6.3.3 Post peak Compression Response

For better understanding of cemented clayey soil-rubber fibre mixtures in post peak region, the normalization of load and deformation axis of axial load-deformation curves has been done with respect to peak axial load (denominated as P_P) and deformation corresponding to peak axial load (denominated as d_P). The variation of normalized load with normalized deformation of clayey soil mixed with 3% and 6% cement and 0%, 2.5%, 5%, 7.5%, and 10% rubber fibres, cured for 28 days (unsoaked condition) are shown in Figs. 6.12 and 6.13. The normalized load -normalized deformation curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber fibres and cured for 7 and 14 days (unsoaked condition) are shown in Appendix (Figs. A41 to A44). The effect of cement content on post-peak load of clayey soil has already been discussed in Chapter 5, Section 5.3.3. Study of Figs. 6.10 and 6.11 clearly shows a gradual decline after attainment of peak in the normalized load – deformation curve of clayey soil-cement-rubber fibres mixtures. A similar behavior of clayey soil-cement-rubber fibres mixtures in soaked conditions was observed as evident from Figs. 6.12 and 6.13. The reason of transformation of sharp drop in post peak axial load of cemented clayey to gradual decline with the incorporation of rubber fibres has already been mentioned in chapter 5, section 5.3.3. Further, curves of the clayey soil-cement-rubber fibres mixtures (soaked condition) cured for 7 and 14 days included in Appendix (Figs. A45 and A48) also show similar gradual decline after attainment of peak in the normalized load – deformation curve.

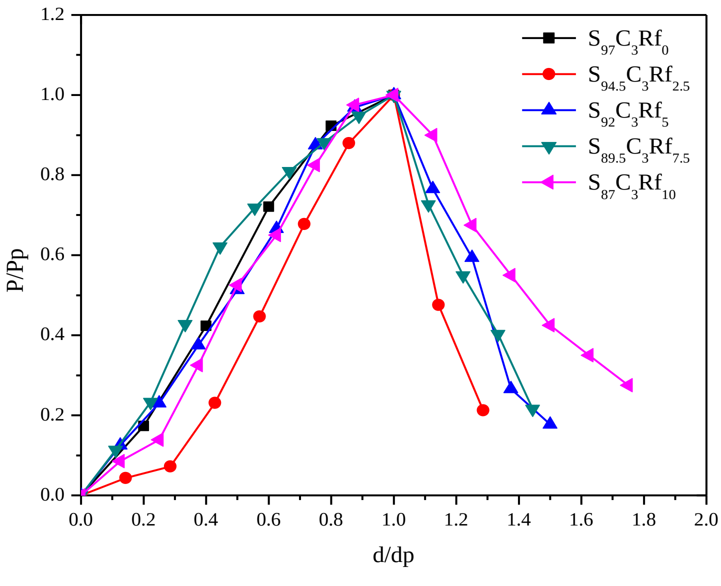


Fig. 6.10 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 28 days (Unsoaked condition)

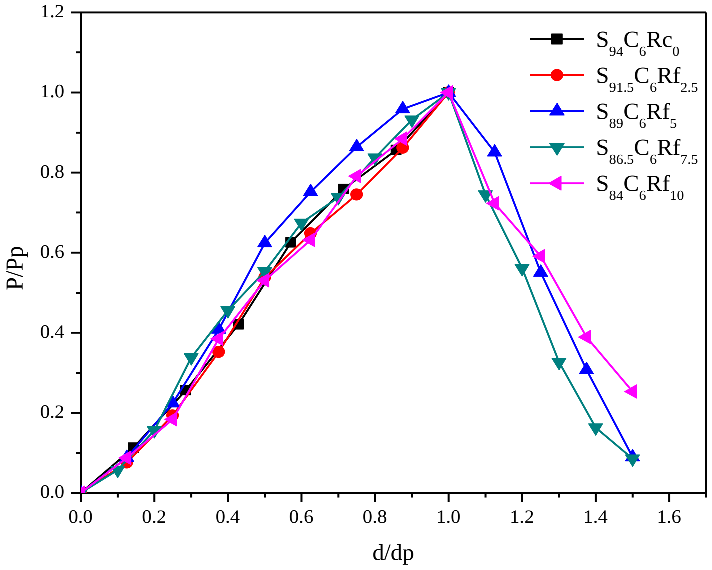


Fig. 6.11 Normalized axial load- deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 28 days (Unsoaked condition)

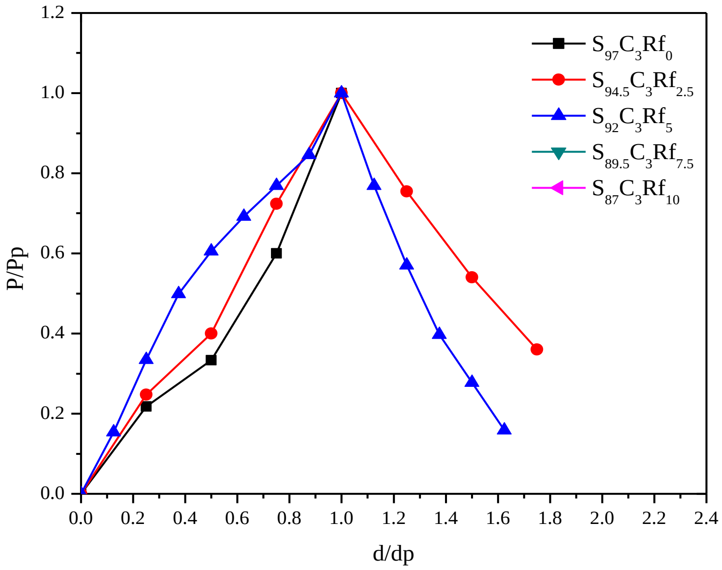


Fig. 6.12 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 28 days (Soaked condition)

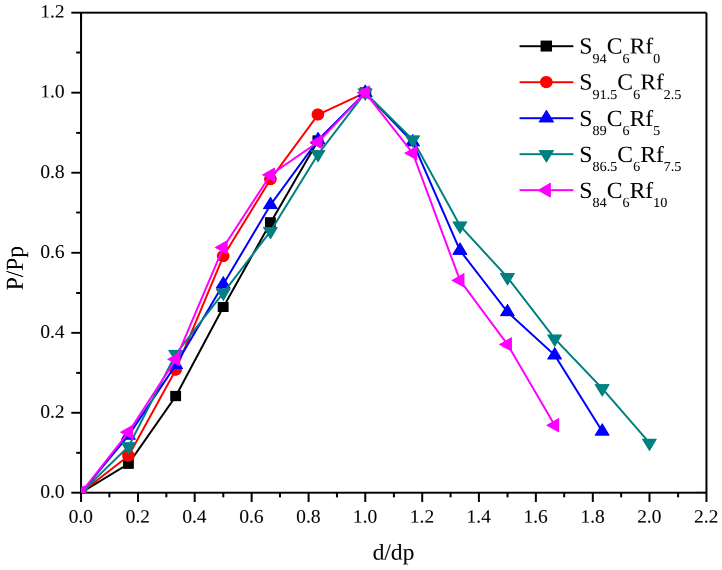


Fig. 6.13 Normalized axial load- deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 28 days (Soaked condition)

6.3.4 Toughness Index in unconfined compression

Table 6.2 Toughness index of clayey soil mixed with cement and rubber fibres

Cement Content (%)	**Curing period (days)**	**Toughness index**									
		Unsoaked condition					**Soaked condition**				
		Rubber fibres content (%)					**Rubber fibres content (%)**				
		0	**2.5**	**5**	**7.5**	**10**	**0**	**2.5**	**5**	**7.5**	**10**
3	7	0	0.299	0.503	0.660	0.654	0	0.239	NA	NA	NA
	14	0	0.313	0.523	0.763	0.750	0	0.293	0.460	NA	NA
	28	0	0.370	0.664	0.783	0.761	0	0.382	0.550	NA	NA
6	7	0	0	0.685	0.785	0.669	0	0	0.473	0.523	0.508
	14	0	0	0.709	0.851	0.767	0	0	0.555	0.554	0.514
	28	0	0	0.789	0.872	0.824	0	0	0.570	0.620	0.566

***** NA- Not applicable due to disintegration of specimen

The toughness index in compression was calculated up to a maximum of 0.0055 m of axial deformation. Table 6.2 shows the values of toughness index of clayey soil mixed with 3% and 6% cement and 0%. 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured at 7, 14, and 28 days for both unsoaked and soaked conditions. It can be seen from Table 6.2 that the value of toughness index is zero of cemented clayey soil specimens. Table 6.2 shows that the toughness index of clayey soil-cement-rubber fibres mixtures increases with the increase in rubber fibres content up to 7.5%. For example, TI of unsoaked specimen $S_{94.5}C_3Rf_{2.5}$ was 0.370 which increased to 0.604, 0.783 and 0.761 for specimens$S_{92}C_3Rf_5$, $S_{89.5}C_3Rf_{7.5}$, and $S_{87}C_3Rf_{10}$, respectively. A study of Table 6.2 further reveals an increase in toughness index with the increase in curing period. For example, for 7 days cured specimen $S_{89}C_6Rf_5$, the value of toughness index was 0.685, which increased to 0.709 and 0.789 with the increase in curing period to 14 and 28 days. Similar trend of increase in toughness index of soaked clayey soil-cement-rubber fibres specimens were observed with the increase in cement content and curing period. For example, 28 days' toughness index of soaked specimen $S_{92}C_3Rf_5$ was 0.550, which increased to 0.570 for specimen $S_{89}C_6Rf_5$. The toughness index of 7 days cured soaked specimen $S_{89}C_6Rf_5$ was 0.473, which increased to 0.555 and 0.570 with the change in curing period to 14 and 28 days.

6.3.5 Pattern of cracking in compression

Figs. 6.14(a) to 6.14(f) show the failure characteristics of 28 days cured clayey soil-cement-rubber fibres specimens. The failure pattern of 28 days cured specimen of clayey soil containing 3% and 6% cement has already been shown in Fig. 5.14(a) and 5.14(b), respectively. The specimen$S_{94.5}C_3Rf_{2.5}$ exhibited typical shear plane failure, which may be responsible for sudden loss of post peak strength after attainment of peak load as shown in Fig. 6.5. In contrast to this, the specimens $S_{92}C_3Rf_5$ and $S_{89.5}C_3Rf_{7.5}$ show multiple cracks as shown in Fig. 6.14(b) and 6.14(c), respectively and this may be responsible for reduction in the rate of loss of post peak strength as shown in Fig. 6.5. For specimen $S_{91.5}C_6Rf_{2.5}$, the vertical crack failure is observed, which may lead to sudden failure of the specimen and no post-peak resistance as shown in Fig. 6.6. The specimen $S_{89}C_6Rf_5$ exhibited a bulging failure with broad vertical cracks as shown in Fig. 6.14(e) may be responsible for sudden decrease of post peak load. Whereas, multiple cracks are observed in the specimen $S_{86.5}C_6Rf_{7.5}$ as shown in Fig. 6.14(f). Overall, the multiple/ staggered cracks are observed in specimens containing both cement and rubber fibres which consequently prevent the sudden failure of the composite. The multiple cracks in specimen may be due to the development of tensile stresses at the surface of rubber fibres, and lower young modulus of rubber fibres (Guleria and Dutta, 2011). The "bridge" effect induced by rubber fibre prevents the development of shear plane, increases the ductility of mixes and contributes to bear stress even after peak (Fig. 6.15).

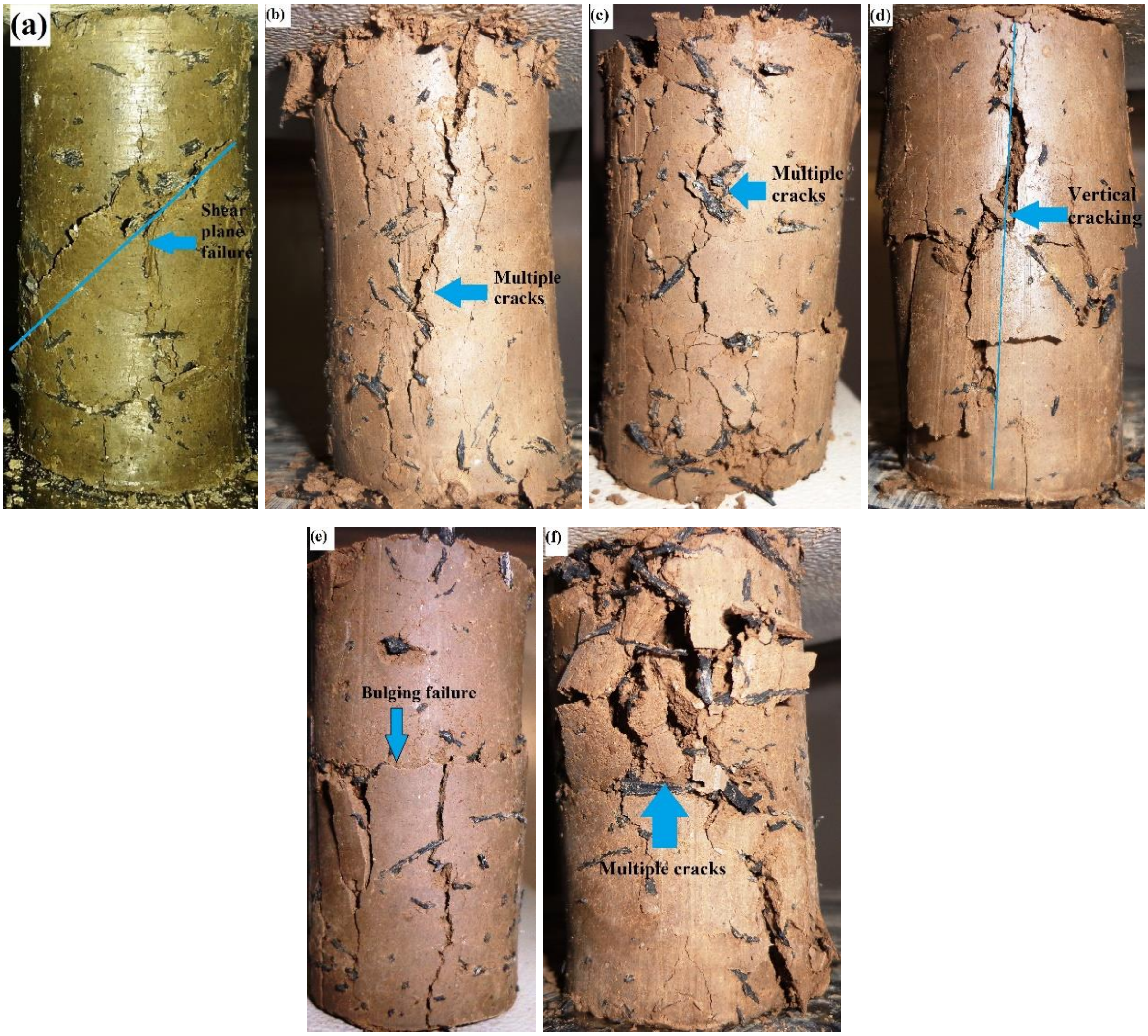


Fig. 6.14 Typical failure patterns of 28 days cured specimens under unconfined compressive strength test (Unsoaked condition)**:** **(a)** $S_{94.5}C_3Rf_{2.5}$, **(b)** $S_{92}C_3Rf_5$, **(c)** $S_{89.5}C_3Rf_{7.5}$, **(d)** $S_{91.5}C_6Rf_{2.5}$, **(e)** $S_{89}C_6Rf_5$, **(f)** $S_{86.5}C_6Rf_{7.5}$

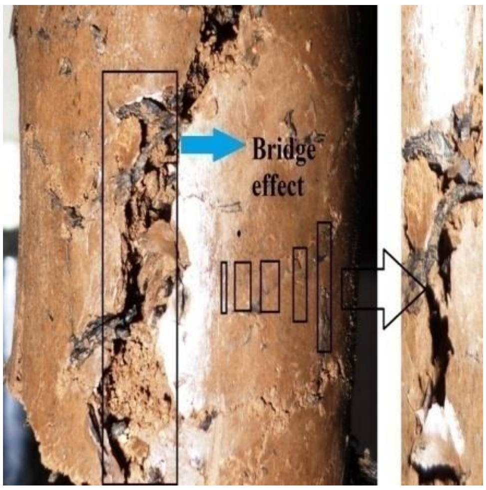


Fig. 6.15 The “bridge” effect included by rubber fibre

Figs. 6.16(a) to 6.16(f) show the effects of cement and rubber fibres content on failure pattern of the soaked specimens. For specimen $S_{94.5}C_3Rf_{2.5}$ and$S_{89}C_6Rf_5$, the bulging with vertical cracks and fissures are observed as shown in Fig. 6.16(a) and 6.16(b). Contrary to this in specimen $S_{91.5}C_6Rf_{2.5}$, vertical crack is observed which may be responsible for the sudden loss of post peak strength as shown in Fig. 6.8. The specimen $S_{89}C_6Rf_5$ and $S_{86.5}C_6Rf_{7.5}$ develop multiple cracks all around the specimen surface, which leads to the peeling of cemented clay at failure condition. In specimen $S_{84}C_6Rf_{10}$, continues bulging is observed as shown in Fig. 6.16(f), which may be responsible for strain hardening behaviour as shown in Fig. 6.8.

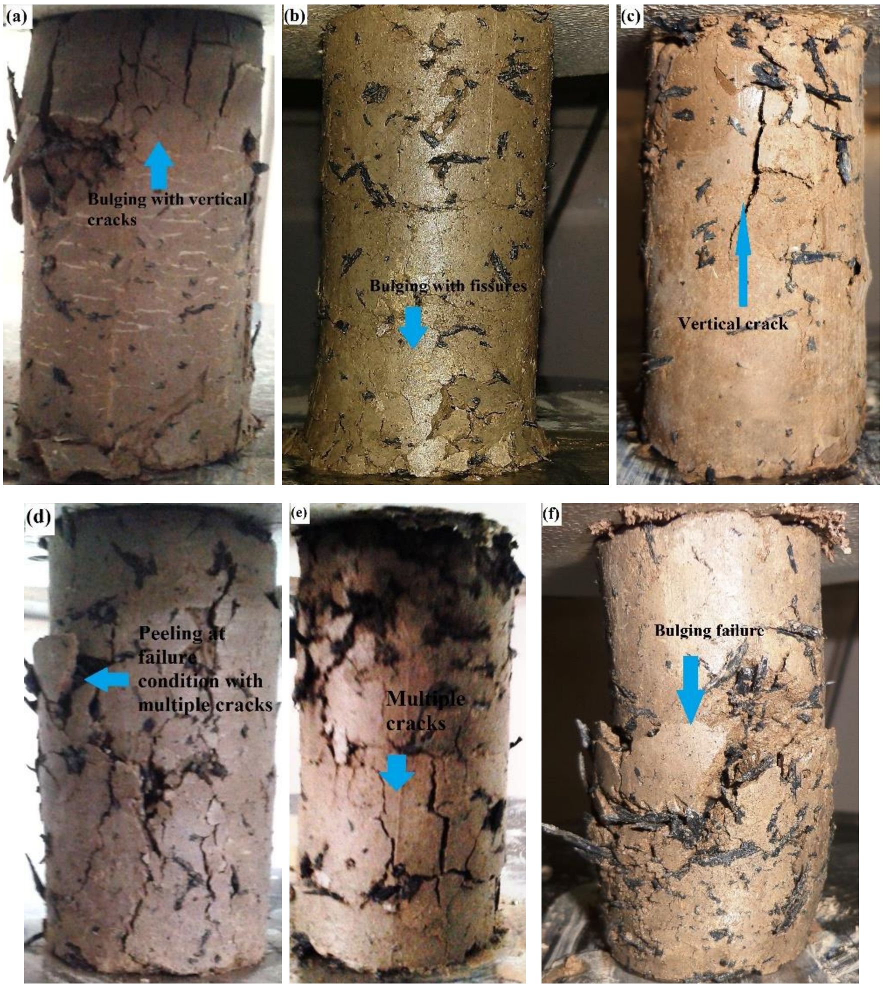


Fig. 6.16 Typical failure patterns of 28 days cured specimens under unconfined compressive strength test (Soaked condition)**: (a)** $S_{94.5}C_3Rf_{2.5}$, **(b)** $S_{92}C_3Rf_5$, **(c)** $S_{91.5}C_6Rf_{2.5}$, **(d)** $S_{89}C_6Rf_5$, **(e)** $S_{86.5}C_6Rf_{7.5}$, **(f)** $S_{84}C_6Rf_{10}$

6.3.6 Unconfined Compressive Strength

The variation of unconfined compressive strength of clayey soil-cement-rubber fibres mixtures with the different age of curing for both unsoaked and soaked condition are shown in Figs. 6.17 to 6.20. It can be seen from Figs. 6.17 and 6.18 that the unconfined compressive strength of mixes increases with the increase in percentage of cement and curing period. The unconfined compressive strength of 7 days cured specimen $S_{91.5}C_6Rf_{2.5}$ was276.5 kPa, which increased to 356.45 kPa and 376.53 kPa if curing period was prolonged from14 to 28 days. However, the rate of strength increment is non-linear and found more during initial days of curing. The unconfined compressive strength of clayey soil-cement-rubber fibres mixtures depends upon primary and secondary cementitious products. The primary products such as C_3S_2Hx (hydrated gel) and $Ca(OH)_2$ is responsible for early strength and hardening of the composite. Whereas, secondary products such as calcium silicate hydrate (C-S-H), and calcium aluminate hydrate (C-A-H) enhance the strength on later stage of curing. With the immersion in water, the unconfined compressive strength of the clayey soil-cement-rubber fibres mixture decreases as shown in Figs. 6.19 and 6.20. For example, the unconfined compressive strength was 347.66 kPa for specimen $S_{89}C_6Rf_5$ in unsoaked condition, which decreased to 235.26 kPa after immersion.

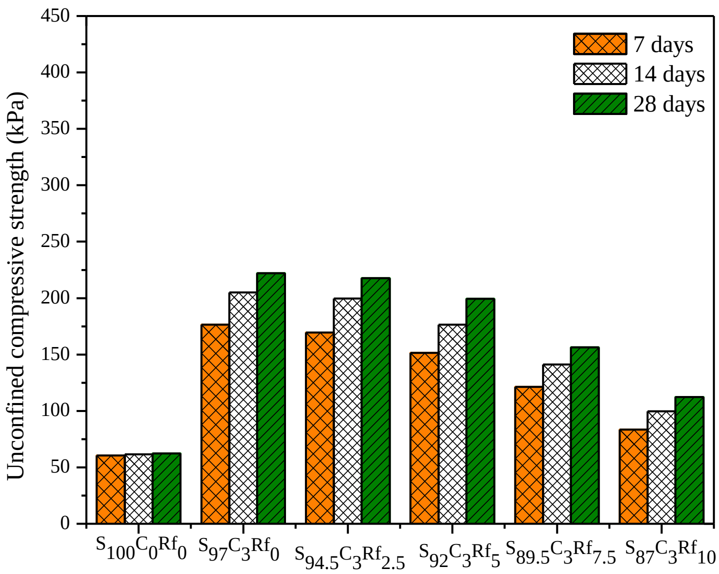


Fig. 6.17 Variation of unconfined compressive strength of clayey soil mixed with 3% cement and rubber fibres and cured for 7, 14, and 28 days (Unsoaked condition)

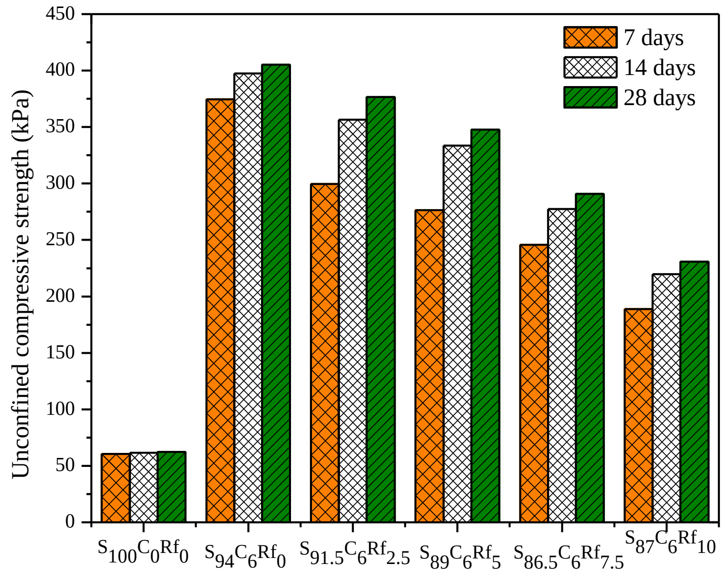


Fig. 6.18 Variation of unconfined compressive strength of clayey soil mixed with 6% cement and rubber fibres and cured for 7, 14, and 28 days (Unsoaked condition)

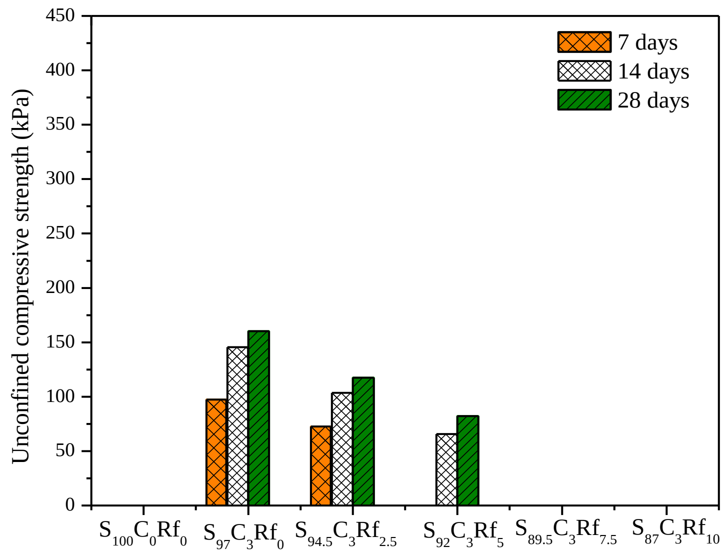


Fig. 6.19 Variation of unconfined compressive strength of clayey soil mixed with 3% cement and rubber fibres and cured for 7, 14, and 28 days (Soaked condition)

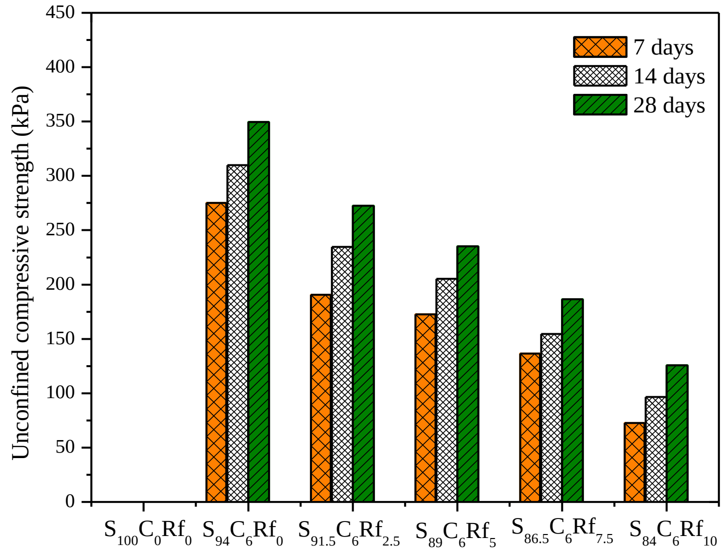


Fig. 6.20 Variation of unconfined compressive strength of clayey soil mixed with 6% cement and rubber fibres and cured for 7, 14, and 28 days (Soaked condition)

Similar to the unconfined compressive strength of clayey soil-cement-rubber crumbles mixtures, the unconfined compressive strength of clayey soil-cement-rubber fibres mixtures decreases with the increase in rubber fibres content. For example, the unconfined compressive strength of 28 days cured unsoaked specimen $S_{94.5}C_6Rf_{2.5}$was 376.53 kPa, which decreased to 347.66 kPa, 290.72 kPa, and 230.68 kPa for specimens $S_{89}C_6Rf_5$, $S_{86.5}C_6Rf_{7.5}$, and $S_{84}C_6Rf_{10}$, respectively. The reason of strength reduction due to inclusion of rubber fibre has already been discussed in section 5.3.6 of chapter 5. Figs. 6.19 and 6.20 show the similar trend of reduction in unconfined compressive strength of the specimens. For example, the unconfined compressive strength of 28 days cured soaked specimen $S_{94.5}C_6Rf_{2.5}$was 276.56 kPa, which decreased to 235.26 kPa, 186.56 kPa, and 125.6 kPa for specimens $S_{89}C_6Rf_5$, $S_{86.5}C_6Rf_{7.5}$, and $S_{84}C_6Rf_{10}$, respectively.

6.4. TENSION BEHAVIOUR

6.4.1. Load - Diametral Deformation Response

The tensile load - diametral deformation response of cement stabilized clayey soil incorporated with/without 2.5%, 5%, 7.5%, and 10% rubber fibres and cured for 28 days are shown in Figs. 6.21 and 6.22 (unsoaked condition). The tensile load - diametral deformation curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber fibres and cured in humidity controlled room for 28 days followed by immersion in water for 24 hrs are shown in Figs. 6.23 and 6.24 (soaked condition). The curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber fibres cured for 7 and 14 days for both unsoaked and soaked condition are shown in Appendix (Figs. A49 to A56). The effect of inclusion of rubber fibres on tensile load - diametral deformation behaviour of clayey soil has already been discussed in section 4.4 of chapter 4.

The effect of inclusion of cement (3% and 6%) on tensile load - diametral deformation behaviour of clayey soil specimens cured for 28 days has already been discussed in chapter 5, section 5.4.1. The tensile load - diametral deformation plots of clayey soil-cement-rubber fibres mixtures cured for 28 days (unsoaked condition) are shown in Figs. 6.21 and 6.22. The variation of tensile load of mixtures is on the same guidelines as that of axial load in compression. The peak tensile load of clayey soil-cement-rubber fibres decreases as the amount of rubber fibres increases. For example, the peak split tensile stress of specimen $S_{94.5}C_3Rf_{2.5}$was 0.315 kN, which reduced to 0.253 kN, 0.166 kN, and 0.105 kN for specimens $S_{92}C_3Rf_5$, $S_{89.5}C_3Rf_{7.5}$, and $S_{87}C_3Rf_{10}$, respectively. The reason of decreases in tensile load has already been explained in the section 5.3.1, chapter 5. Similar trend of reduction in peak tensile load was observed for soaked specimens of clayey soil-cement-rubber fibres mixtures with the increase in rubber fibres content as shown in Figs. 6.23 and 6.24. For example, for soaked specimen $S_{94}C_6Rf_0$, the peak tensile load was 0.412 kN, which decreased to 0.354 kN, 0.321 kN, 0.266 kN, and 0.1605 kN for specimens $S_{91.5}C_6Rf_{2.5}$, $S_{89}C_6Rf_5$, $S_{86.5}C_6Rf_{7.5}$, and$S_{84}C_6Rf_{10}$, respectively. The reason of reduction in tensile load of soaked specimens has already been discussed in the section 5.3. of chapter 5.

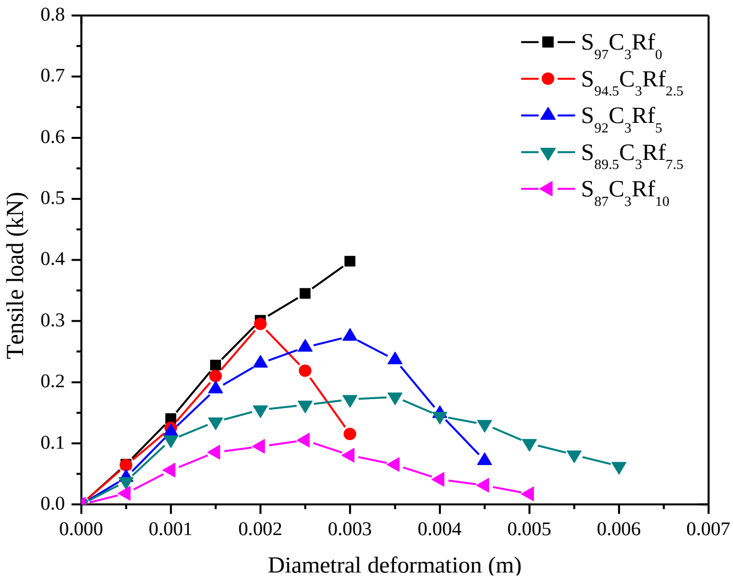


Fig. 6.21 Tensile load-diametral deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 28 days (Unsoaked condition)

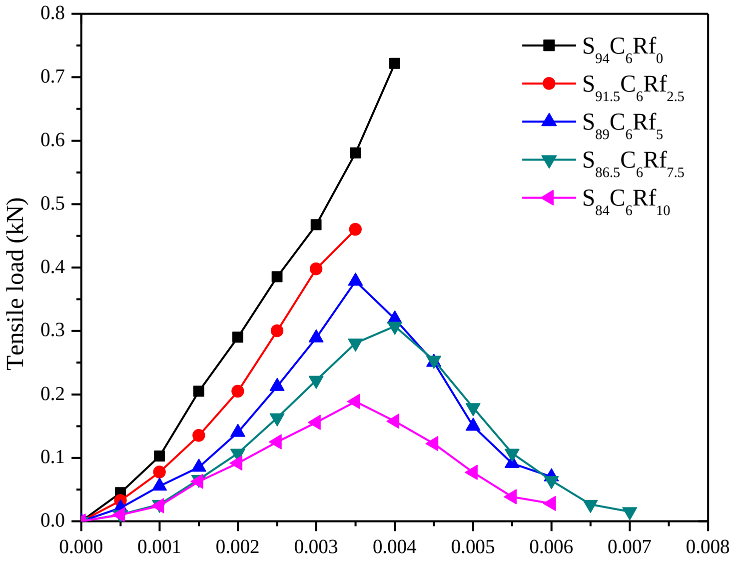


Fig. 6.22 Tensile load-diametral deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 28 days (Unsoaked condition)

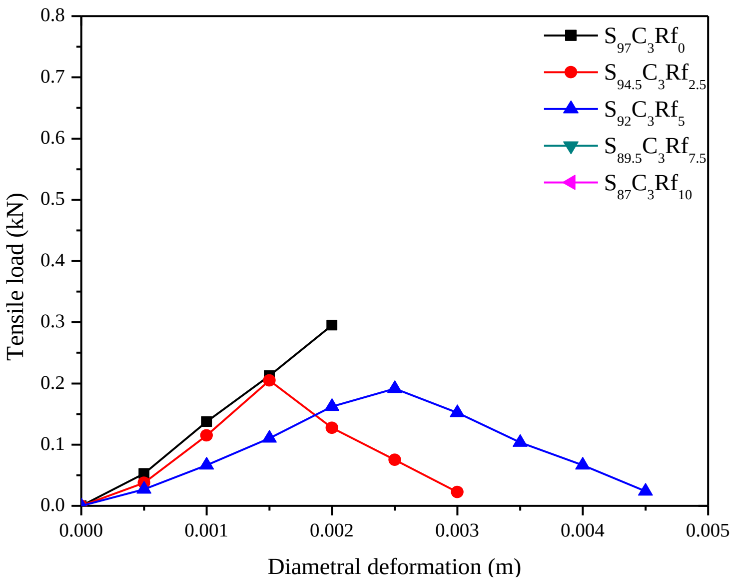


Fig. 6.23 Tensile load-diametral deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 28 days (Soaked condition)

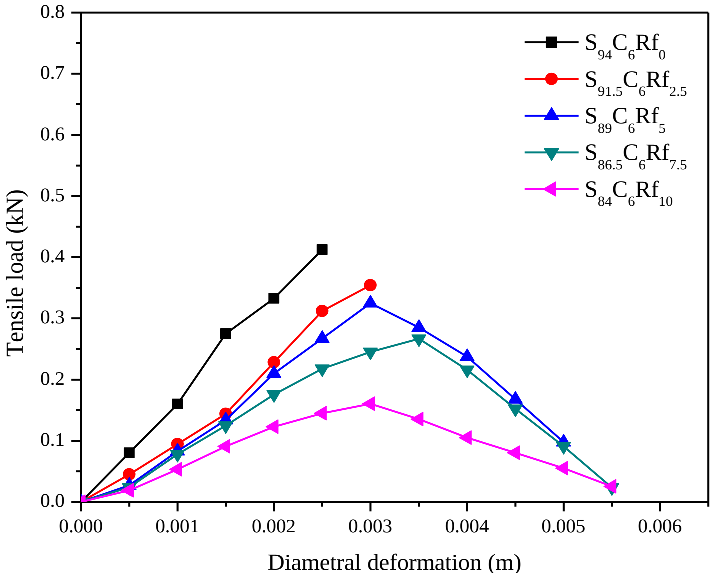


Fig. 6.24 Tensile load-diametral deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 28 days (Soaked condition)

The peak diametral deformations of clayey soil-cement-rubber fibres mixtures under tensile load are on same guideline of peak axial deformation in compression. A close examination of Figs. 6.21 and 6.23 reveals that the increase in diametral deformation was highest with inclusion of 7.5% rubber fibres in cement stabilized clayey-rubber fibres mixtures. A similar trend was observed for soaked specimens of clayey soil-cement-rubber crumbles mixtures as well shown in Figs. 6.23 and 6.24.

Study of Fig. 6.21, Fig. 6.22 and Appendix (Figs. A17 to A20) further reveals that the diametral deformation of clayey soil-cement-rubber fibres mixture increases with the increase in curing period. For example, the diametral deformation at failure of 7 and 14 day cured unsoaked specimen $S_{92}C_3Rf_{7.5}$ was 0.003 m and 0.0035 m, which increased to 0.0035 mm with the change in curing period to 28 days. Similar trend of increase in diametral deformation with the increase in curing period was observed for soaked specimens as shown in Figs. 6.23 and 6.24 and Appendix (Figs. A21 to A24).

A close examination of Fig. 6.21, Fig. 6.22 and Appendix (Figs. A49 to A52) reveals that the peak tensile load of clayey soil-cement-rubber fibres specimen's increases with the increase in curing period. For example, the peak tensile load of 7 days cured specimen $S_{92}C_3Rf_5$ in unsoaked condition was 0.234 kN, which increased to 0.261 kN and 0.315 kN after 14 and 28 days of curing, respectively. The curves of soaked specimens as shown in

Figs. 6.23 and 6.24 and Appendix (Figs. A53 to A56) have also shown the similar trend of increase in peak tensile load with the increase in curing period.

6.4.2. Absolute toughness in tension

The values of absolute toughness of clayey soil mixed with 3% and 6%cement and 0%. 2.5%, 5%, 7.5%, and 10% rubber fibres and cured at 7, 14, and 28 days are shown in Table 6.3 for both unsoaked and soaked conditions.

The effect of cement content on absolute toughness of clayey soil has already been discussed in section 5.4.2. of chapter 5. An examination of Table 6.3 shows that the absolute toughness of clayey stabilized with 3% cement, increases with the increase in rubber fibres content up to 5%. For example, from Table 6.3, the absolute toughness of 28 days cured specimen $S_{94.5}C_3Rf_{2.5}$ was 0.000273 kN.m, which increased to a value of 0.000488 kN.m for specimen $S_{92}C_3Rf_5$. Further incorporation of rubber fibres in clayey soil stabilized with 3% cement decreases the absolute toughness. Whereas a continuous reduction in the absolute toughness of clayey soil stabilized with 6% cement containing rubber fibres is observed. For example, the absolute toughness of 28 days cured specimen $S_{91.5}C_6Rf_{2.5}$ was 0.000688 kN.m, which decreased to 0.000491 kN.m, 0.000486 kN.m and 0.000282 kN.m for specimen $S_{89}C_6Rf_5$, $S_{86.5}C_6Rf_{7.5}$, and $S_{84}C_6Rf_{10}$, respectively. Table 6.3 further shows an increase in absolute toughness of clayey soil-cement-rubber fibres mixtures with the increase in curing period. For example, for specimen $S_{91.5}C_6Rf_{2.5}$, the absolute toughness of 0.0004587 kN.m at 7 days of curing increased to 0.000624 kN.m and 0.000688 kN.m with the increase in curing period to 14 and 28 days. Similar trend of increase in absolute toughness of soaked clayey soil-cement-rubber fibres specimens were observed with the increase in cement content and curing period as evident in Table 6.3. For example, 28 days' absolute toughness of soaked specimen $S_{94.5}C_3Rf_{2.5}$ was 0.000127 kN.m, which increased to 0.0005 kN.m for specimen$S_{91.5}C_6Rf_{2.5}$. The absolute toughness of 7 days cured soaked specimen $S_{89}C_6Rf_5$ was 0.000269 kN.m, which increased to0.000334 kN.m and 0.000441 kN.m with the change in curing period to 14 and 28 days.

Table 6.3 Absolute toughness in tension of clayey soil mixed with cement and rubber fibres

Cement Content (%)	Curing period (days)	Absolute toughness (kN.m x 10^{-4})									
		Unsoaked condition					Soaked condition				
		Rubber fibres content (%)					Rubber fibres content (%)				
		0	2.5	5	7.5	10	0	2.5	5	7.5	10
3	7	4.080	2.466	2.901	2.145	0.954	2.095	1.146	NA	NA	NA
	14	6.094	2.655	3.390	3.237	1.480	2.537	1.237	1.863	NA	NA
	28	6.351	2.732	4.882	3.606	1.532	2.749	1.275	2.306	NA	NA
6	7	6.224	4.587	3.618	3.175	1.598	3.572	3.148	2.693	2.109	1.678
	14	8.062	6.247	4.722	4.707	2.613	4.881	4.025	3.341	2.532	1.774
	28	8.927	6.887	4.961	4.869	2.822	5.268	5.001	4.417	4.189	2.554

***** NA- Not applicable due to disintegration of specimen

6.4.3. Post peak Tensile Response

The variation of normalized tensile load with normalized diametral deformation of cemented clayey soil mixed with/without 2.5%, 5%, 7.5%, and 10% rubber fibres, cured for 28 days (unsoaked condition) are shown in Figs. 6.25 and 6.26. The normalized tensile load - normalized daimetral deformation curves of cement stabilized clayey soil mixed with 2.5%, 5%, 7.5%, and 10% rubber fibres and cured in humidity controlled room for 28 days followed by immersion in water for 24 hrs are shown in Figs. 6.27 and 6.28 (soaked condition).The normalized tensile load-normalized daimetral deformation curves of cement stabilized clayey soil mixed with/without 2.5%, 5%, 7.5%, and 10% rubber crumbles and cured for 7 and 14 days for both unsoaked and soaked condition are shown in Appendix (Figs. A57 to A64).

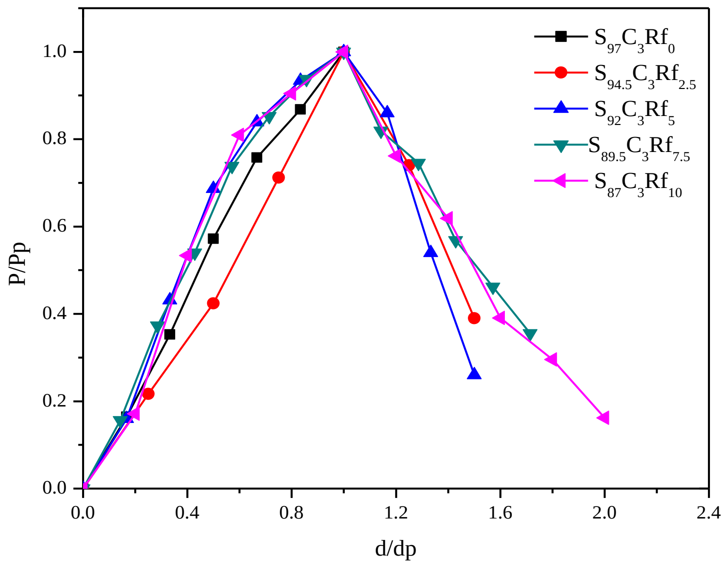


Fig. 6.25 Normalized tensile load-deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 28 days (Unsoaked condition)

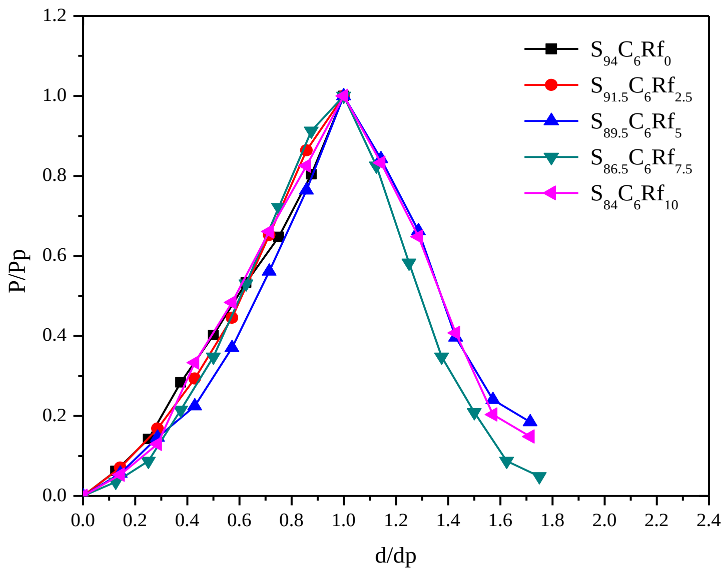


Fig. 6.26 Normalized tensile load-deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 28 days (Unsoaked condition)

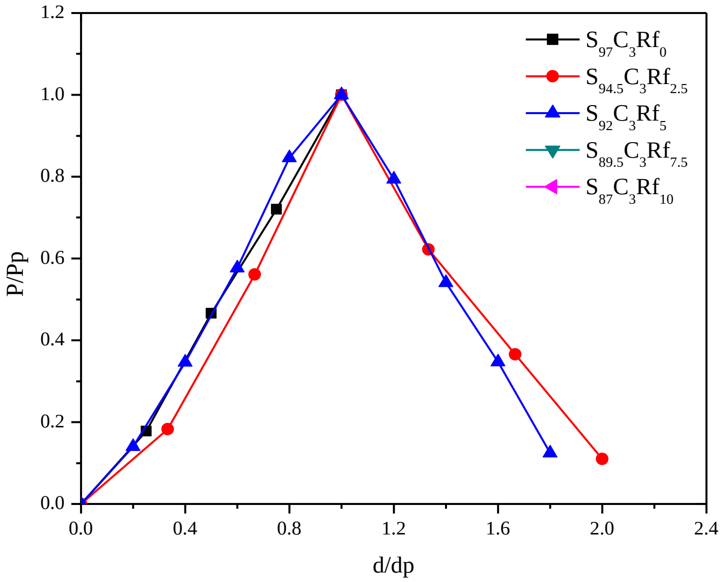


Fig. 6.27 Normalized tensile load-deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 28 days (Soaked condition)

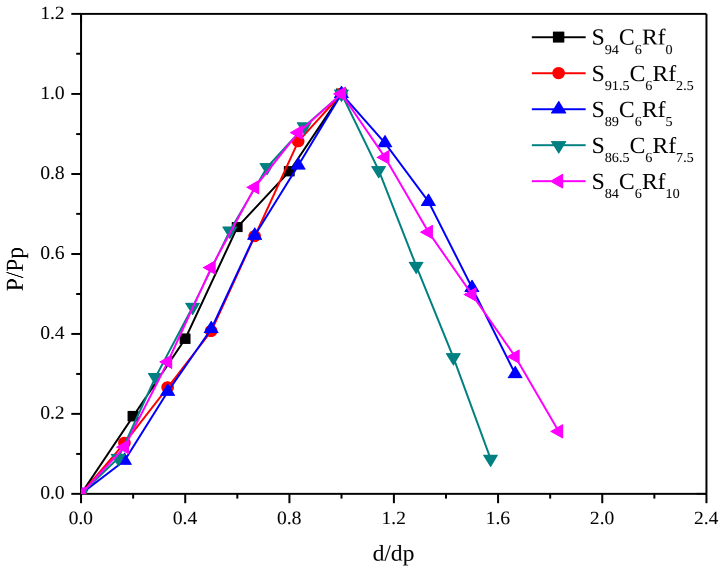


Fig. 6.28 Normalized tensile load-deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 28 days (Soaked condition)

The effect of cement content on normalized tensile load-deformation of the clayey soil has already been discussed in chapter 5 of section 5.4.3. Contrary to the normalization tensile load curves of cemented clayey, the clay incorporated with both cement and rubber fibres were observed to follow a gradual decline after attaining peak in the normalized tensile load-diametral deformation curves. It indicates the effectiveness of rubber fibres in improving the behaviour of cemented clay (i.e. brittle to ductile) under tensile loads. Similar post peak behaviour of clayey soil-cement-rubber fibres specimens cured for 7 and 14 days as evident from Appendix (Figs. A57 to A60) for unsoaked condition was observed. Besides this, soaked specimens of clayey soil-cement-rubber fibres mixtures shown in Figs. 6.27 and 6.28 and Appendix (Figs. A61 to A64) have also shown similar behaviour as that of unsoaked specimens. Thus from the above, it can be concluded that inclusion of rubber fibres in the cemented clayey soil improve its post-peak behaviour in tension.

6.4.4. Toughness Index in Tension

The values of toughness index of clayey soil mixed with 3% and 6% cement and 0%, 2.5%, 5%, 7.5%, and 10% rubber fibres and cured at 7, 14, and 28 days are shown in Table 6.4 for both unsoaked and soaked conditions. The toughness index in compression was calculated up to a maximum of 0.0055 m of diametral deformation.

Table 6.4 Toughness index in tension for clayey soil mixed with cement and rubber fibres

Cement Content (%)	Curing period (days)	Toughness index									
		Unsoaked condition					Soaked condition				
		Rubber fibres content (%)					Rubber fibres content (%)				
		0	**2.5**	**5**	**7.5**	**10**	**0**	**2.5**	**5**	**7.5**	**10**
3	7	0	0.250	0.392	0.550	0.441	0	0.192	NA	NA	NA
	14	0	0.328	0.406	0.662	0.476	0	0.223	0.374	NA	NA
	28	0	0.359	0.444	0.715	0.484	0	0.245	0.456	NA	NA
6	7	0	0	0.530	0.634	0.456	0	0	0.409	0.466	0.416
	14	0	0	0.567	0.694	0.566	0	0	0.512	0.524	0.511
	28	0	0	0.630	0.746	0.622	0	0	0.554	0.565	0.542

***** NA- Not applicable due to disintegration of specimen

The toughness index of cemented clayey soil increases with the inclusion of rubber fibres content up to 7.5%. Further incorporation of rubber fibres decreases the toughness index. For example, TI of the 3% cemented clay containing 5.0% rubber fibres and 6% cemented clay containing 5.0% rubber were 0.444 and 0.630, which increased to 0.715 and 0.746 for the cemented clay (3% and 6% cement content) incorporated with 7.5% rubber fibres, respectively. A study of Table 6.4 further reveals an increase in toughness index with increase in curing period. For example, 7 days cured specimen $S_{92}C_3Rf_{7.5}$, the toughness index was0.555, which increased to 0.662 and 0.715 with the increase in curing period to 14 and 28 days. Similar increase in the toughness index as evident in Table 6.4 was also observed for soaked clayey soil-cement-rubber fibres specimens with the increase in cement content and curing period. For example, 28 days' toughness index of soaked specimen $S_{92}C_3Rf_5$ was 0.456, which increased to 0.554 for specimen $S_{89}C_6Rf_5$. The toughness index of 7 days cured soaked specimen $S_{86.5}C_6Rf_{7.5}$ was 0.466, which increased to 0.524 and 0.565 with the change in curing period to 14 and 28 days.

6.4.5 Cracking Pattern in Tension

The effect of cement content on cracking patterns of 28 days cured specimens of cemented clayey soil has already been discussed in chapter 5, section 5.4.5. Figs. 6.29(a) to 6.29(f) show the cracking patterns of 28 days cured specimens $S_{94.5}C_3Rf_{2.5}$, $S_{92}C_3Rf_5$, $S_{89.5}C_3Rf_{7.5}$, $S_{89}C_6Rf_5$, and $S_{86.5}C_6Rf_{7.5}$ under tensile load. Contrary to catastrophic failure of the cemented clayey, failure patterns of clayey soil-cement-rubber fibre specimens have been found different. Besides, the rubber fibres have been randomly mixed with cement and clayey soil, but sometimes the rubber fibres may get confined/orientated to a certain planes/ areas, which change the path of crack propagation. Whereas, the staggerally located rubber fibres may lead to triangular failure pattern of the specimens. The diagrammatic views of both types of failure patterns are shown in Fig. 6.30. The vertical crack as shown in Fig. 6.29(a) of specimen $S_{94.5}C_3Rf_{2.5}$ may be due to the alignment of rubber fibres in vertical direction. Whereas multiple cracking patterns in the form of triangle of specimen $S_{89.5}C_3Rf_{7.5}$, and $S_{89}C_6Rf_5$ as shown in Figs. 6.29(c) and 6.29(d) and staggered cracks shown in Figs. 6.29(b) and 6.29(e) for specimen $S_{92}C_3Rf_5$ and $S_{86.5}C_6Rf_{7.5}$ may be due to lower young's modulus of rubber fibres as compared to the cemented clay. The difference in young's modulus of rubber fibres and cemented clay may cause the non-uniform deformation when the specimens are subjected to tensile stresses. The multiple cracking patterns help specimens to bear load even after the failure. Further, such specimens were observed to fail with higher deformation rate before undergoing final collapse/failure. The confinement provided by rubber fibres to the cemented clay do not allow the specimens to split into two halves which helps to bear tensile stresses even after attainment of peak tensile load (Fig. 6.29(f)).

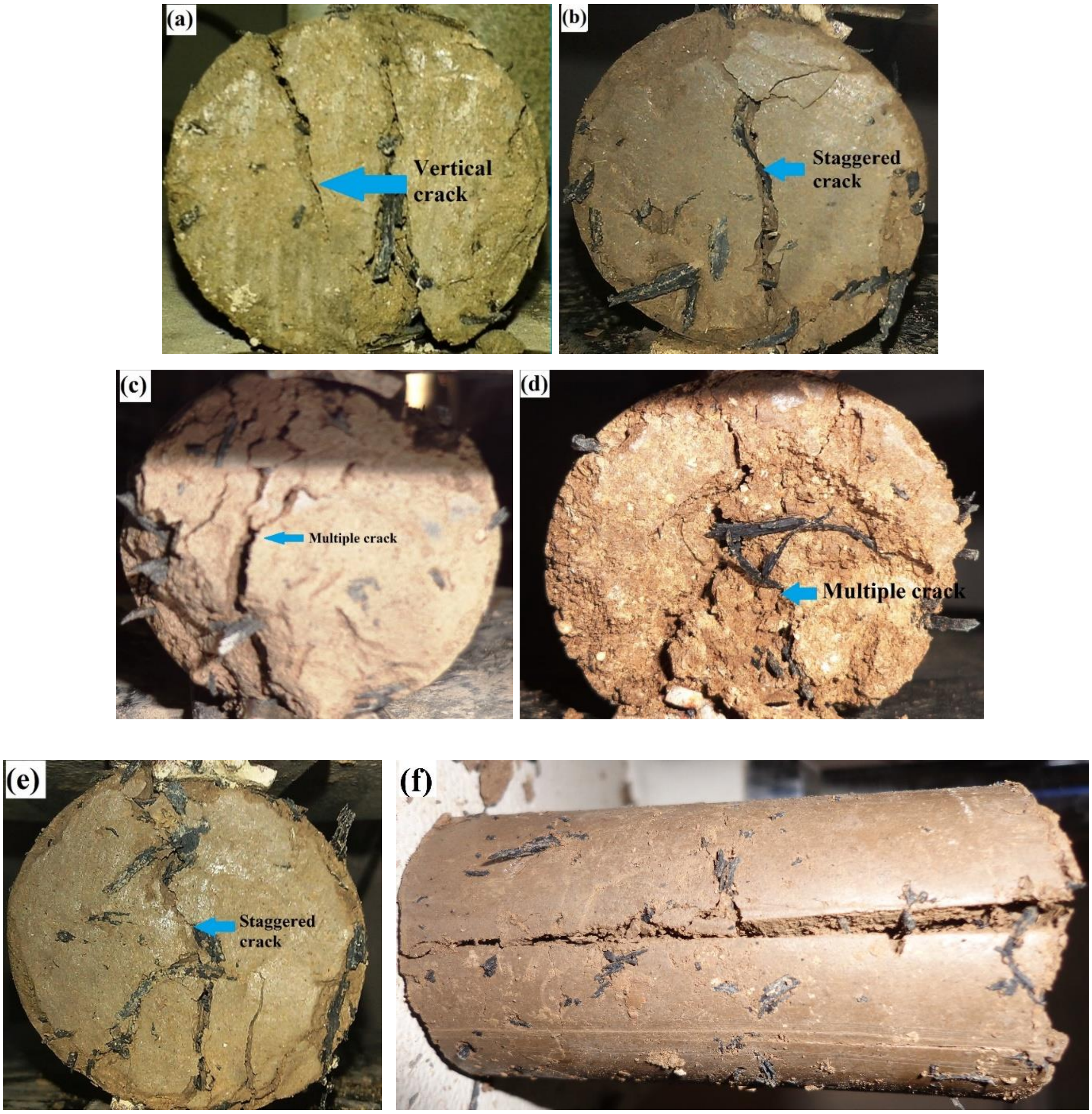


Fig. 6.29 Typical failure patterns of 28 days cured specimens under split tensile strength test (Unsoaked condition)**:** **(a)** $S_{94.5}C_3Rf_{2.5}$, **(b)** $S_{92}C_3Rf_5$, **(c)** $S_{89.5}C_3Rf_{7.5}$, **(d)** $S_{89}C_6Rf_5$, **(e)** $S_{86.5}C_6Rf_{7.5}$, **(f)** $S_{89}C_6Rf_5$

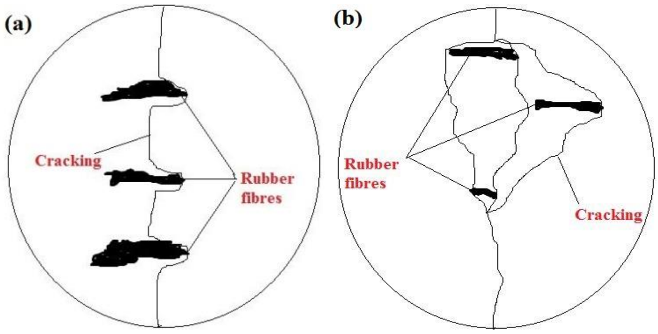


Fig. 6.30 Schematic sketch of cracking pattern **(a)** vertically aligned rubber fibres; **(b)** staggerally located rubber fibres

Similar to the unsoaked specimens, the soaked specimens of clayey soil-cement-rubber fibres mixtures shows multiple cracks as shown in Fig. 6.31.

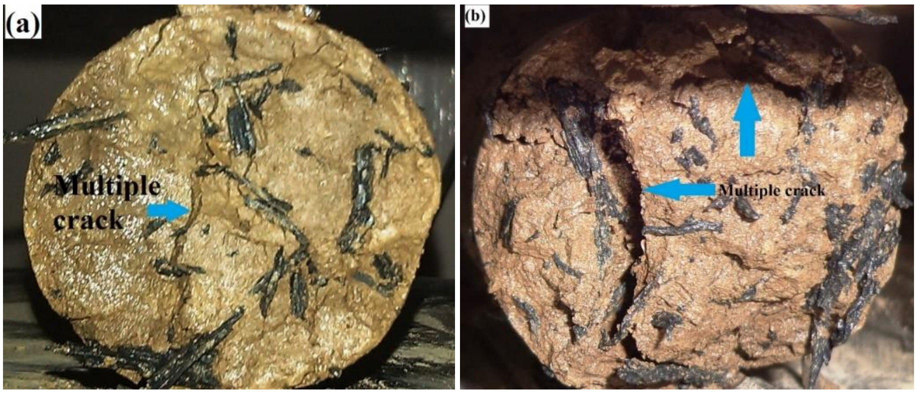


Fig. 6.31 Typical failure patterns of 28 days cured specimens under split tensile strength test (Soaked condition): **(a)** $S_{92}C_3Rc_5$, **(b)** $S_{86.5}C_6Rc_{7.5}$

6.4.6. Split Tensile Strength

The results of split tensile strength of clayey soil-cement-rubber fibres mixtures cured for 7, 14 and 28 days both unsoaked and soaked condition are shown in Figs. 6.32 to 6.35.

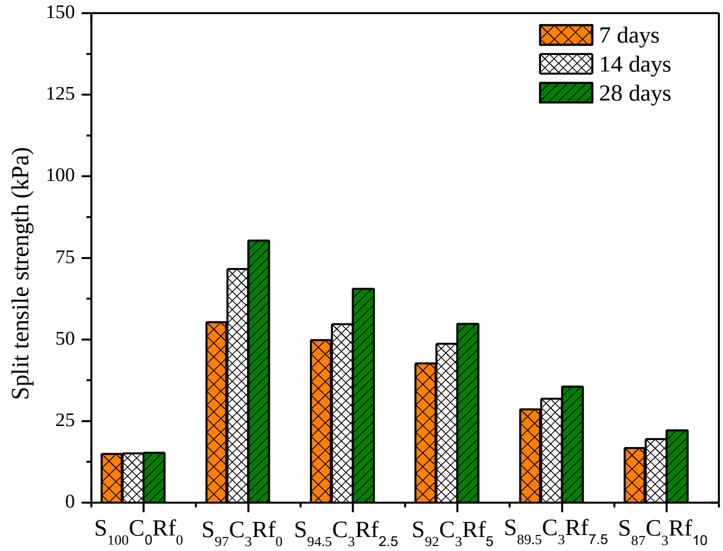


Fig. 6.32 Variation of split tensile strength of clayey soil mixed with 3% cement and rubber fibres and cured for 7, 14, and 28 days (Unsoaked condition)

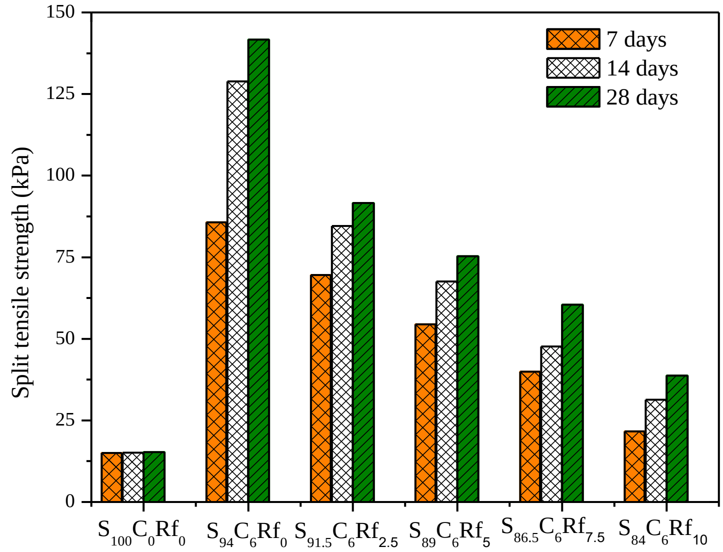


Fig. 6.33 Variation of split tensile strength of clayey soil mixed with 6% cement and rubber fibres and cured for 7, 14, and 28 days (Unsoaked condition)

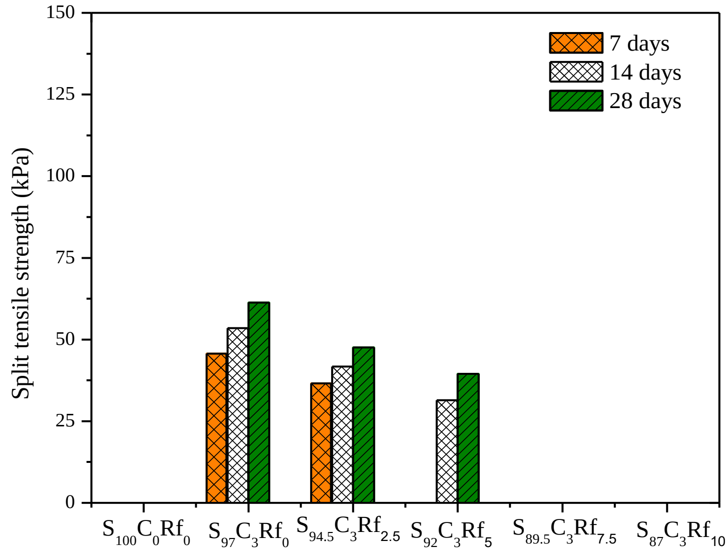


Fig. 6.34 Variation of split tensile strength of clayey soil mixed with 3% cement and rubber fibres and cured for 7, 14, and 28 days (Soaked condition)

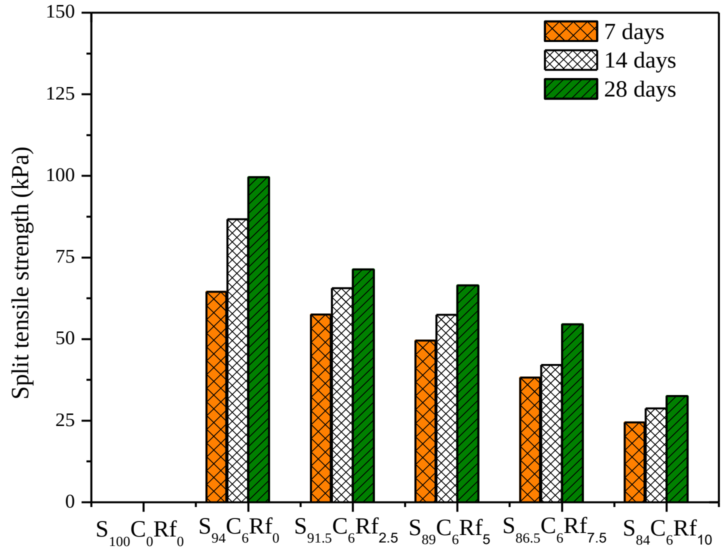


Fig. 6.35 Variation of split tensile strength of clayey soil mixed with 6% cement and rubber fibres and cured for 7, 14, and 28 days (Soaked condition)

A study of Figs. 6.32 and 6.33 reveals an increase in split tensile strength of clayey soil-cement-rubber fibres mixtures with the increase in cement content and curing time. For example, the split tensile strength of 7 days cured specimen $S_{91.5}C_6Rf_{2.5}$ was 69.59 kPa, which increased to 84.56 kPa and 91.59 kPa with prolongation of curing age from 14 to 28 days. Again, this may be accredited to the formation of primary and secondary cementitious products. Similar trend of increase in split tensile strength of clayey soil-cement-rubber fibres mixtures with the increase in cement content and curing time was observed for soaked specimens as shown in Figs. 6.34 and 6.35.

A study of Figs. 6.32 and 6.33 reveals a decrease in the tensile strength with the increase in rubber fibres content. For example, the split tensile strength of 28 days cured specimen $S_{94.5}C_3Rf_{2.5}$was 65.48 kPa, which decreased to 54.78 kPa, 35.56 kPa, and 16.78 kPa for specimens $S_{92}C_3Rf_5$, $S_{89.5}C_3Rf_{7.5}$, and $S_{87}C_3Rf_{10}$, respectively. The reason of decrease in split tensile strength has been discussed in detail in section 5.4.6 of chapter 5. Similar trend of decrease in split tensile strength of clayey soil-cement-rubber fibres mixtures with the increase in rubber fibres was observed for soaked specimens as shown in Figs. 6.34 and 6.35. For example, the split tensile strength of 28 days cured specimens $S_{94.5}C_3Rf_{2.5}$and $S_{91.5}C_6Rf_{2.5}$was 65.48 kPa and 91.59 kPa in unsoaked conditions, which reduced to 47.76 kPa and 71.35 kPa in soaked condition. The reason of reduction in tensile strength due to soaking has already been discussed in section 5.4.6 of chapter 5.

6.5 CALIFORNIA BEARING RATIO VALUE

The load-penetration curves of clayey soil-cement-rubber fibres mixtures obtained from California Bearing Ratio tests for both unsoaked and soaked conditions are shown in Figs. 6.36 to 6.39.

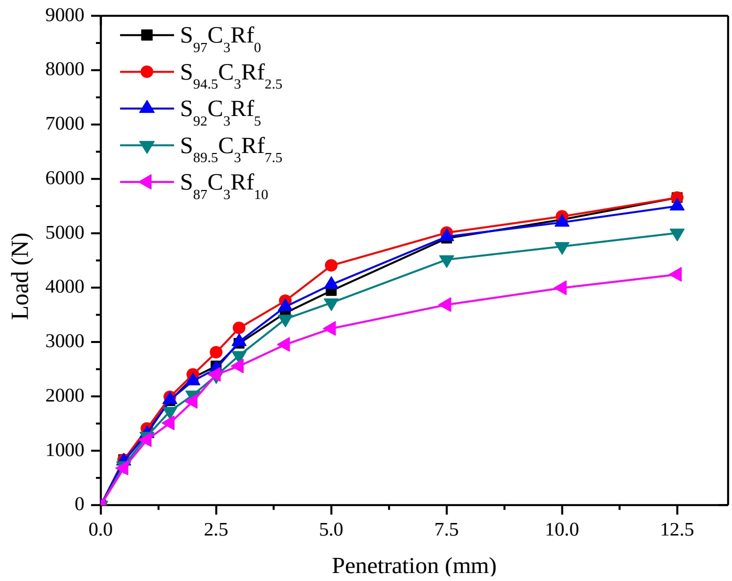


Fig. 6.36 Load- penetration curves of clayey soil mixed with 3% cement and rubber fibres (Unsoaked condition)

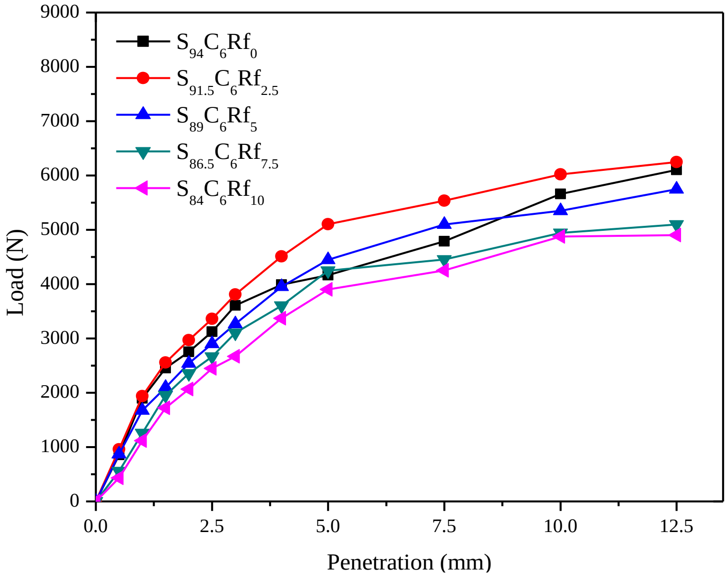


Fig. 6.37 Load- penetration curves of clayey soil mixed with 6% cement and rubber fibres (Unsoaked condition)

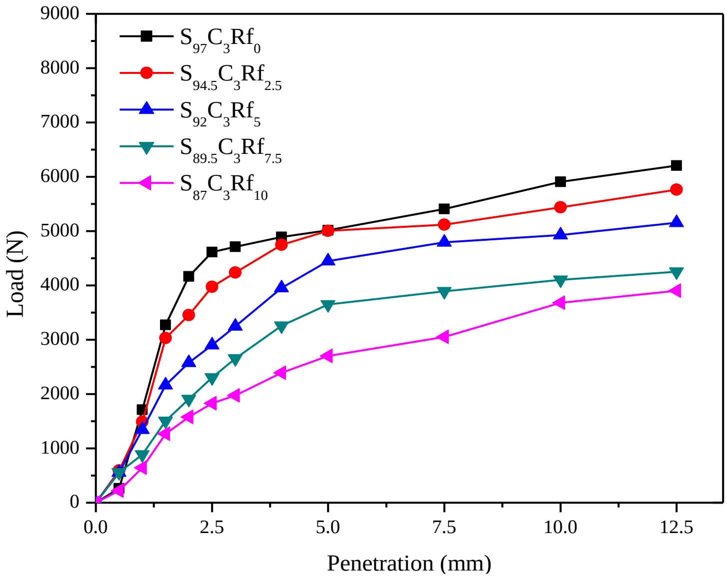


Fig. 6.38 Load- penetration curves of clayey soil mixed with 3% cement and rubber fibres (Soaked condition)

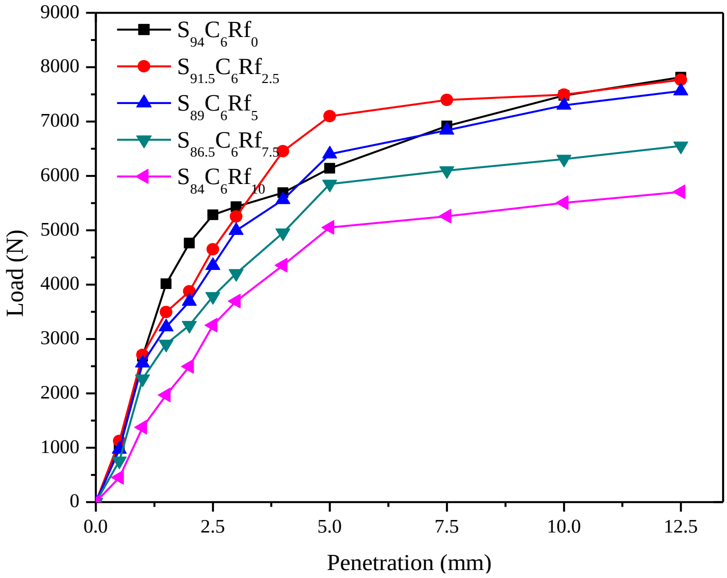


Fig. 6.39 Load- penetration curves of clayey soil mixed with 6% cement and rubber fibres (Soaked condition)

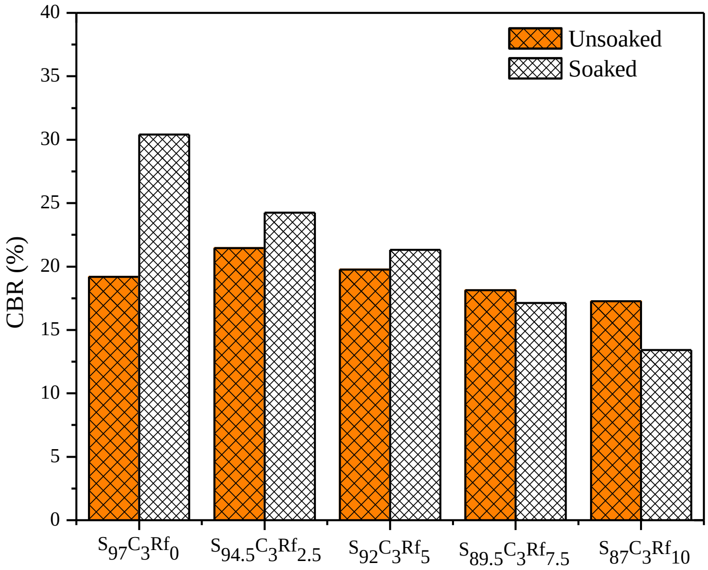


Fig. 6.40 Variation of California Bearing Ratio (%) of clayey soil mixed with 3% cement and rubber fibres

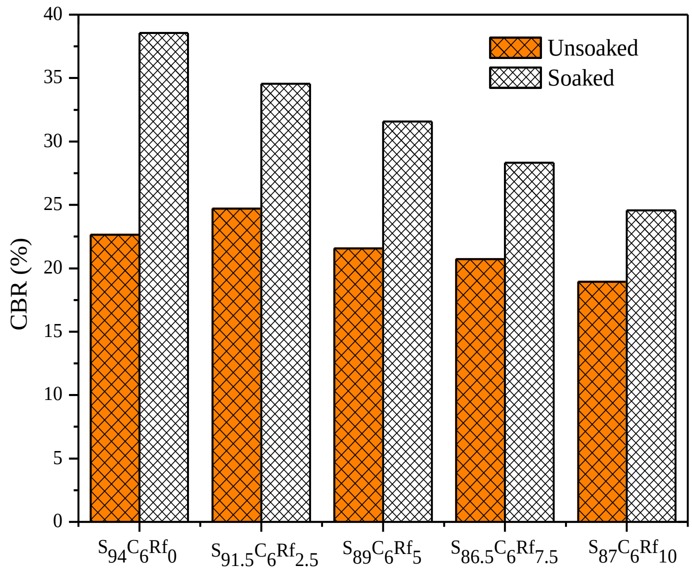


Fig. 6.41 Variation of California Bearing Ratio (%) of clayey soil mixed with 6% cement and rubber fibres

It is observed from Figs. 6.40 and 6.41 that the inclusion of cement increases the CBR value of soil. Unsoaked CBR value of clay increases by 81.20% and 113.03% with the addition of 3% and 6% cement content, respectively. The CBR value of cemented clay obtained in soaked condition is more than unsoaked CBR value. The CBR value of specimens $S_{97}C_3Rf_0$ and $S_{94}C_6Rf_0$ in soaked condition is 3.51 and 4.46 times more than the soaked CBR value of specimen $S_{100}C_0Rf_0$. The improvement in CBR value of clay with the incorporation of cement may due to hydration reaction between cement and clay particles, which harden the mixture and ultimately increase its resistance against the penetration.

The combined effect of rubber fibres and cement on CBR value of clayey soil is presented in Figs. 6.40 and 6.41. In general, the addition of rubber fibres reduces the CBR values of cemented clay. The effect of rubber fibres on unsoaked CBR values of cement-stabilized clay have been found insignificant, approximately. However, it severely affects the soaked CBR values of cemented clay. The soaked CBR value of specimen $S_{97}C_3Rf_0$ decreases by 20.43%, 29.89%, 43.70%, and 55.90% with the inclusion of 2.5%, 5%, 7.5%, and 10% rubber fibres content, respectively. Similarly, the soaked CBR value of $S_{94}C_6Rf_0$ reduces by 10.37%, 18.12%, 26.55%, and 36.46% with the addition of 2.5%, 5%, 7.5%, and 10% rubber fibres content, respectively. The reduction in CBR values of cemented clay with the addition of rubber fibres may due to (i) the reduction in interaction between the cemented clay particles, (ii) less contribution of rubber fibres in strength development.

6.6 ONE-DIMENSIONAL CONSOLIDATION

The vertical strain vs. pressure curves of clayey soil - rubber fibres mixtures treated with 3% and 6% cement are presented in Figs. 6.42 and 6.43, respectively. The data in Table 6.5 show the compression indices of clayey soil-cement-rubber fibres mixtures obtained from the consolidation curves.

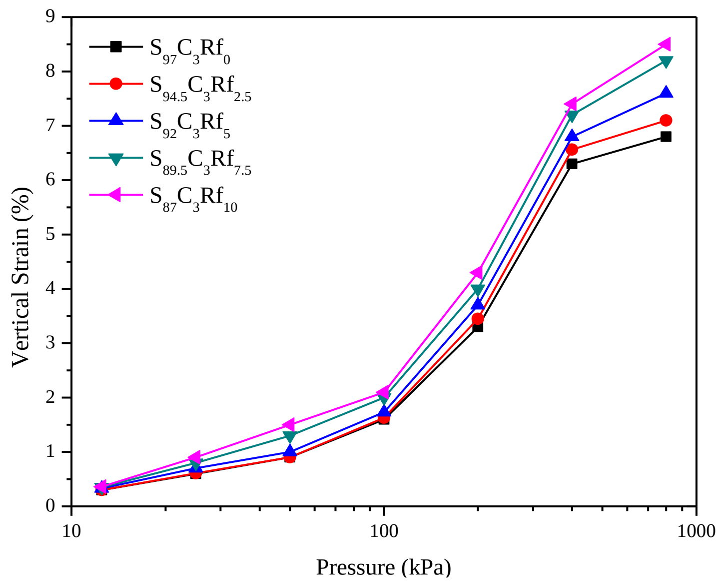


Fig. 6.42 Compression Curves of clayey soil mixed with 3% cement and rubber fibres

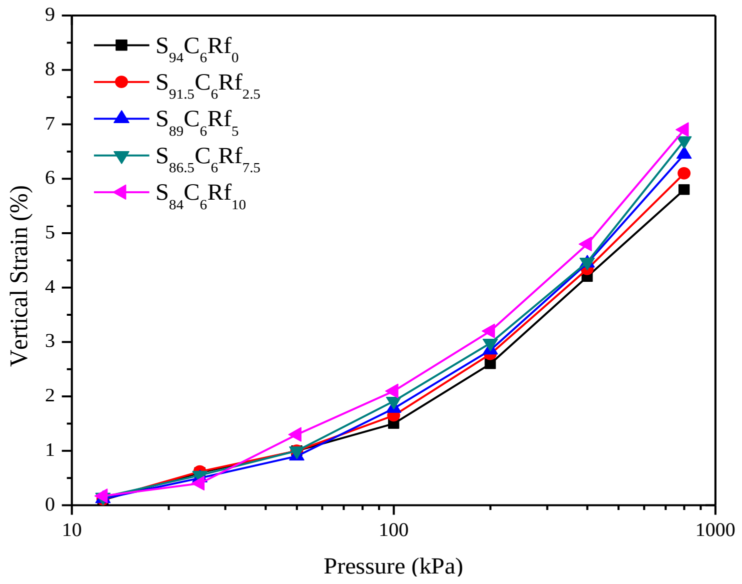


Fig. 6.43 Compression Curves of clayey soil mixed with 6% cement and rubber fibres

The data in the Table 6.5 show that the compression index of cemented clayey soil increases with the inclusion of rubber fibres. Although, the rubber fibres binds cemented clayey soil particles as well as restrict the movements, but at interface of rubber fibres and cemented clayey soil particles gaps are observed (as shown in Fig. 6.51). The presence of gap at interface may lead to increase in void ratio of the composite and could be reason for increased C_C of the mixtures.

Table 6.5 Results of consolidation tests on clayey soil mixed with cement and rubber fibres

Cement content (%)	**Compression index (C_C)**				
	Rubber fibres content (%)				
	0	**2.5**	**5**	**7.5**	**10**
3	0.349	0.352	0.358	0.370	0.392
6	0.192	0.201	0.221	0.231	0.249

6.7 SWELLING PRESSURE

The variation of swelling pressure of clayey soil-cement-rubber fibres mixtures is shown in Fig. 6.44. It can be seen from Fig. 6.44 that the swelling pressure of clay decreases with the increase in cement and rubber fibres content. The effect of inclusion of cement on the swelling pressure of the clayey soil has already been discussed in detail in chapter 5, section 5.7.

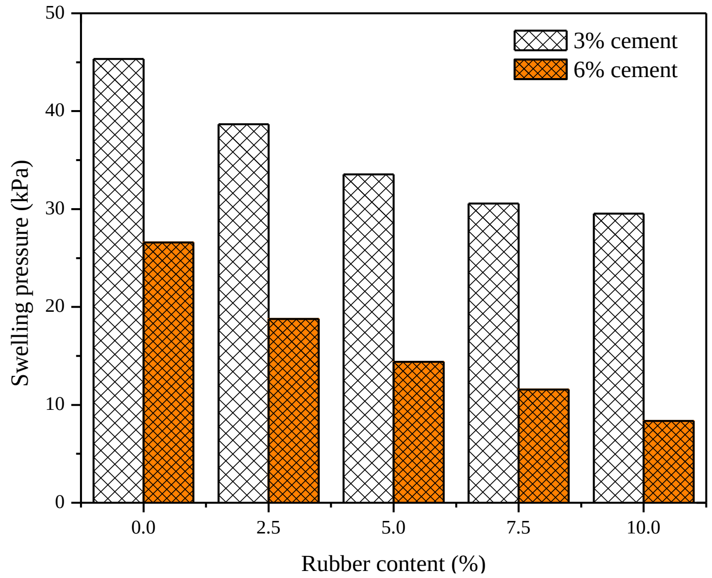


Fig. 6.44 Variation of swelling pressure of clayey soil mixed with cement and rubber fibres

It can be observed from Fig. 6.44 that the inclusion of both cement and rubber fibres decreases, the swelling pressure of clayey soil. The swelling pressure of clayey soil stabilized with 3% cement decreases by 14.71%, 26%, 32.58%, and 34.28% with the addition of 2.5%, 5%, 7.5%, and 10% rubber fibres content. Similarly, the incorporation of 2.5%, 5%, 7.5%, and 10% rubber fibres content lowers the swelling pressure of clayey soil containing 6% cement by 29.57%, 45.86%, 56.50%, and 68.54%, respectively. Reduction in swelling pressure may be due to (i) substitution of swelling clay particles by non-swelling rubber fibres; (ii) reinforcement effect induced by rubber fibres against the tensile stresses of swelling which prevents movement of clay particles attached to the rubber fibres; (iii) cavity in the rubber fibre; (iv) small gap at the interface of rubber fibres and rest of composite, which creates a drainage path for the dissipation of pore water.

6.8 DURABILITY BEHAVIOUR

One of the most important properties that the stabilized soils should have is the ability to retain its strength over the year when exposed to the destructive forces of weather. One of the most commonly used durability tests on stabilized soils in a non-frost area is wetting and drying test. The test result of wet-dry durability in term of weight loss of 7, 28, 90, and 180 days cured specimens plotted against the number of cycles are shown in Figs. 6.45, 6.46, 6.47, and 6.48, respectively.

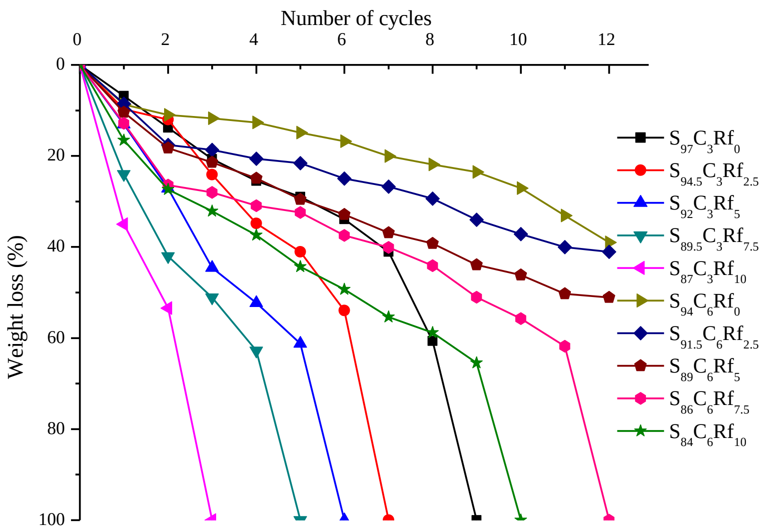


Fig. 6.45 Variation of weight loss- Number of cycles of clayey soil mixed with cement and rubber fibres and cured for 7 days

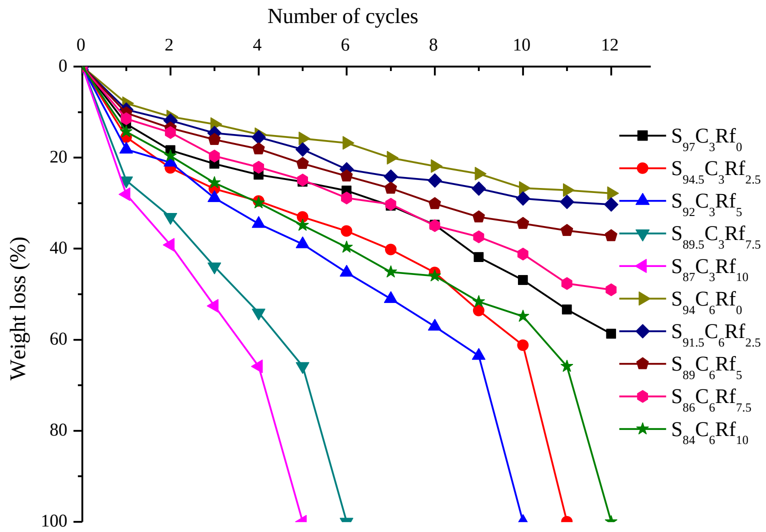


Fig. 6.46 Variation of weight loss- Number of cycles of clayey soil mixed with cement and rubber fibres and cured for 28 days

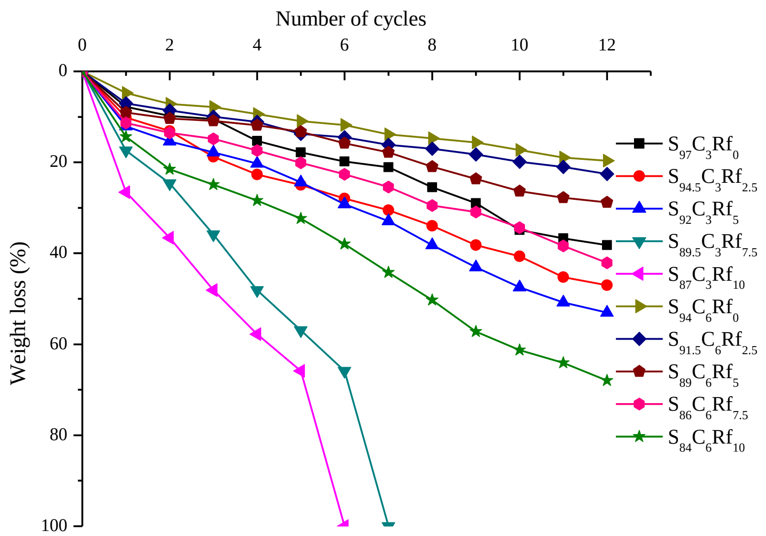


Fig. 6.47 Variation of weight loss- Number of cycles of clayey soil mixed with cement and rubber crumbles and cured for 90 days

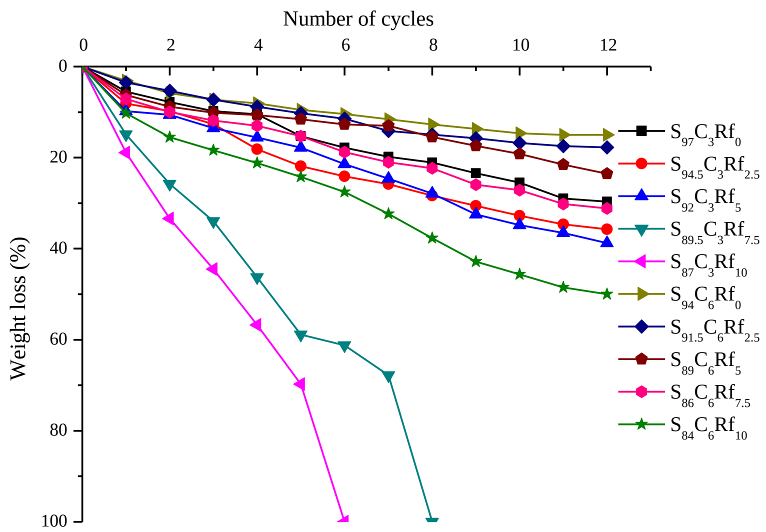


Fig. 6.48 Variation of weight loss- Number of cycles of clayey soil mixed with cement and rubber fibres and cured for 180 days

The uncemented specimen of clay-rubber fibres mixture disintegrates completely during the first wet cycle as mentioned in chapter 4, section 4.8. Similarly, 7 days cured specimens $S_{94.5}C_3Rf_{2.5}$, $S_{92}C_3Rf_5$, $S_{89.5}C_3Rf_{7.5}$, and $S_{87}C_3Rf_{10}$are not able to maintain the volumetric integrity and fails before completion of 12 cycles. The prolongation of curing time of specimens before testing makes the specimens able to endure the complete process with few exceptions as shown in Figs. 6.45 to 6.48. Fig. 6.49 presents the variation of weight loss versus curing time of clayey soil-cement-rubber fibre mixtures. It can be seen from Fig. 6.56 that weight loss of the mixtures decreases with the increase in cement content and curing time. For example, the weight loss of 90 days cured specimen $S_{97}C_3Rf_0$ was 38.2%, which reduced to 19.28% for specimen $S_{94}C_6Rf_0$. The weight loss of 7 days cured specimen $S_{91.5}C_6Rf_{2.5}$ was 41.04%, which reduced to 30.37%, 22.54%, and 17.71%, if curing period of specimen was prolonged from 28 to 90 and 180 days, respectively.

The weight loss of the mixtures increases with the increase in rubber fibre content. The weight loss of 180 days cured $S_{91.5}C_6Rf_{2.5}$specimen was 17.71%, which increased to 21.54%, 30.08% and 50.22% for specimens $S_{89}C_6Rf_5$, $S_{86.5}C_6Rf_{7.5}$, and $S_{84}C_6Rf_{10}$, respectively. Increment in weight loss may be due to (i) non-uniform thermal expansion of rubber fibres and cement stabilized clay during dry cycle, which reduces the bond strength, (ii) voids created by the abrasive action of wire-scratch brush get wider when subjected to wet cycle.

Fig. 6.50 shows the pictorial view of 180 days cured specimens of clayey soil-cement-rubber fibres mixtures during wet/dry cycles.

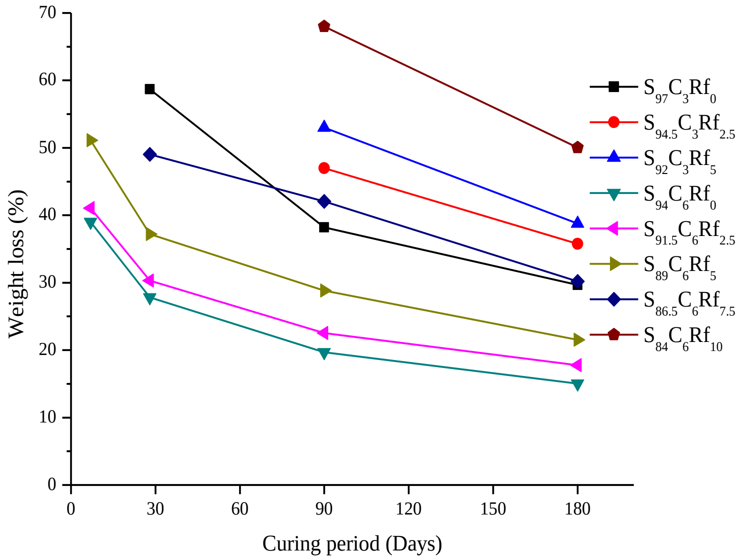


Fig. 6.49 Weight loss- curing period of the composites after completion of 12 wetting and drying cycles

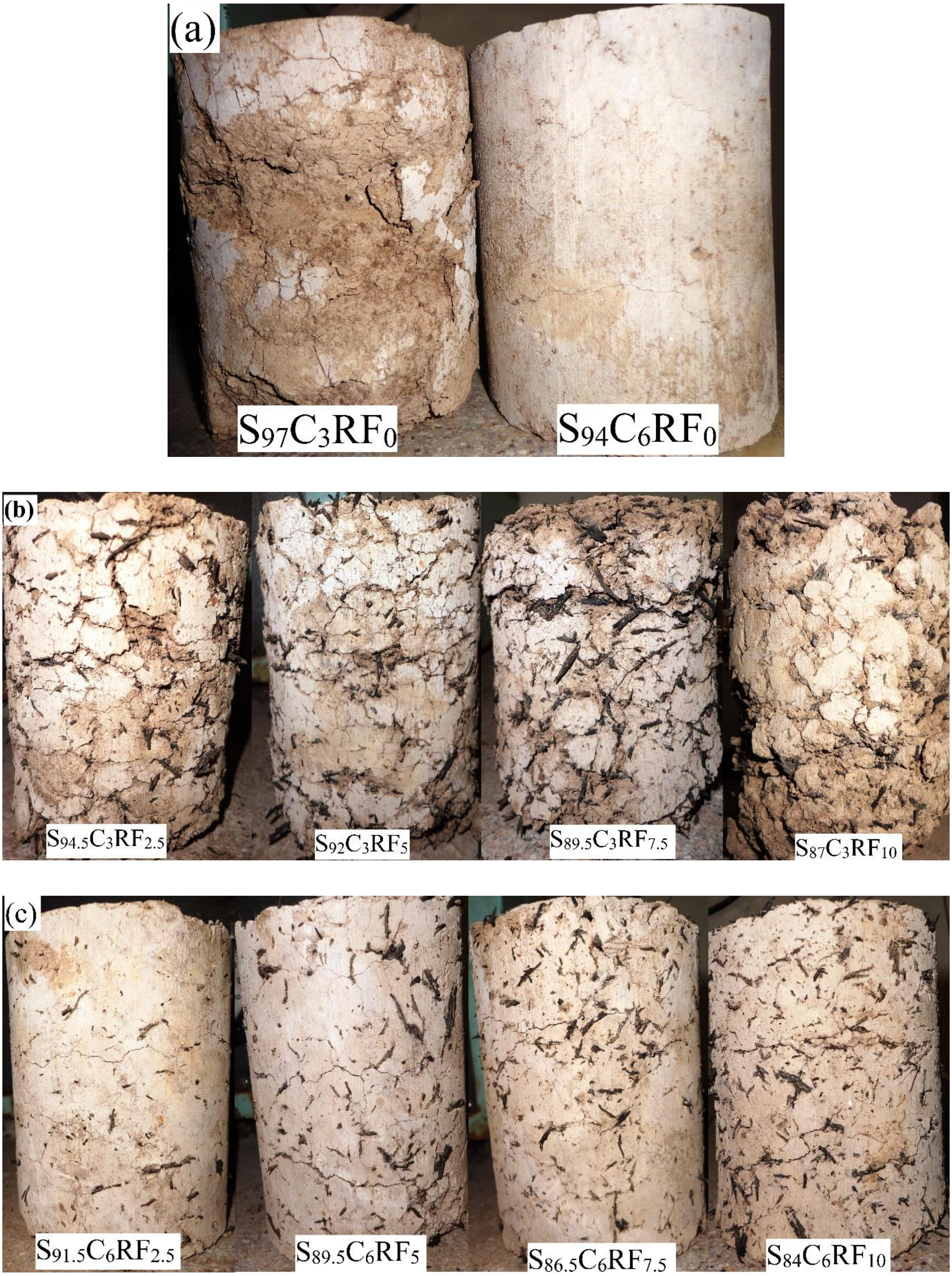


Fig. 6.50 Photographs of the clayey soil-cement-rubber fibre specimens during wetting and drying cycles (180 days cured)

6.9 MINERALOGICAL AND MORPHOLOGICAL STUDIES

In the preceding sections 6.3 to 6.7, it has been seen that the content of cement and rubber fibres affects the unconfined compressive strength, split tensile strength, California Bearing Ratio, compression index, swelling pressure and durability of clayey soil-cement-rubber fibres mixtures. Keeping the above in view, XRD (X-ray diffraction) and SEM (scanning electron micrographs) analysis were carried out on 28 days cured specimens of clayey soil-cement-rubber fibres mixtures. The results of mineralogical studies on clayey soil mixed with 3% and 6% cement content has already been discussed in detail in chapter 5, section 5.9.

6.9.1Morphological Studies

The results of SEM of clayey soil-cement-rubber fibres mixtures are shown Figs. 6.51(a) and 6.51(b). The results of morphological studies on specimen of clayey soil mixed with 3% and 6% cement content has already been discussed in detail in chapter 5, section 5.9.

At the interface of rubber fibres and cemented clay specimens $S_{94.5}C_3Rf_{2.5}$ and $S_{89}C_6Rf_5$, a gap has been seen (Fig. 6.51(a) and 6.51(b)). The cavity and micro-cracks on surface of rubber fibre as shown in chapter 3, section 3.2.3 may responsible for the poor adhesion between cemented clay and rubber fibres, which may lead to gap creation at the interface. The weak interfacial interaction between cemented clay and rubber fibres may be responsible for the reduction in unconfined compressive strength, split tensile strength, and California Bearing Ratio as shown in sections 6.2, 6.3 and 6.4, respectively.

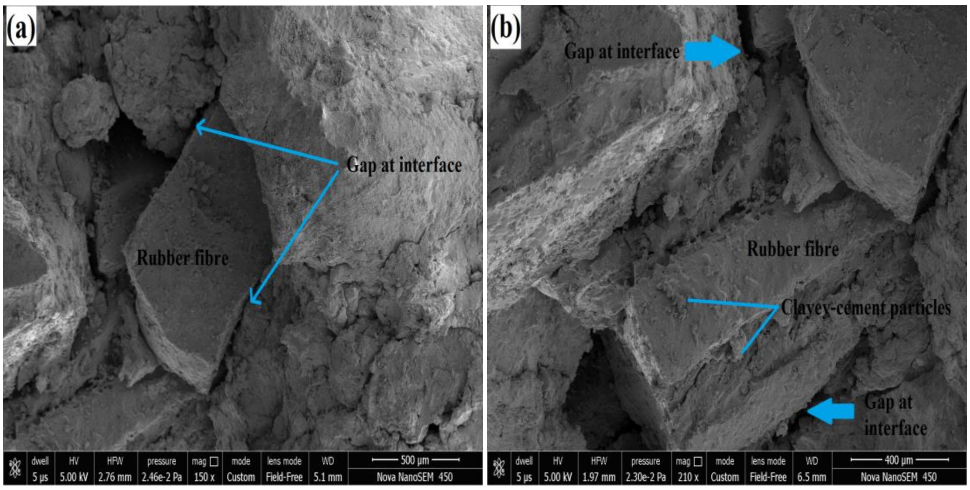


Fig. 6.51 SEM Photograph of specimens cured for 28 days **(a)** $S_{94.5}C_3Rf_{2.5}$ (5KV, 150x, 500 µm), **(b)** $S_{89}C_6Rf_5$ (5KV, 210x, 400 µm)

6.10 STATISTICAL ANALYSIS

Multiple linear regression analysis (MLRA) is used to develop the best relationship between one continuous dependent variable and two or more dependent variables. In the study, Statistical software SPSS 12.0 was used to investigate the relationship between dependent variable and independent variables. A general model for formulating MLRA for a given n observation is given below:

$$\mu_y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots\ldots\ldots\ldots.. + \beta_p x_p \qquad (6.1)$$

Where

μ_y is dependent variable, x_i indicates independent variables and β_i depicts predicted parameters, respectively.

Based on the modified proctor, unconfined compressive strength, split tensile strength, California Bearing Ratio, one-dimensional consolidation, and swelling pressure test results, multiple regression models were developed to predict the maximum dry unit weight, optimum moisture content, unconfined compressive strength, split tensile strength, California Bearing Ratio value, compression index, and swelling pressure of clayey soil-cement-rubber fibres mixtures. The equation for predicating the values of maximum dry unit weight, optimum moisture content, unconfined compressive strength, split tensile strength, California Bearing Ratio value, compression index, and swelling pressure of clayey soil-cement-rubber fibres mixtures are given below:

Maximum dry unit weight (predicted) = 16.433 - 0.051*C - 0.162*Rf (6.2)

Optimum moisture content (predicted) = 20.844 + 0.080*C - 0.300*Rf (6.3)

Unsoaked UCS (Predicted) = 53.935 + 48.231*C - 14.539*Rf+ 2.016*CT (6.4)

Soaked UCS (Predicted) = -53.803 + 50.993*C - 19.250*Rf+ 2.773*CT (6.5)

Unsoaked STS (Predicted) = 42.561 + 7.553*C - 6.768*Rf+ 0.875*CT (6.6)

Soaked STS (Predicted) = 15.742 + 8.869*C - 5.030*Rf + 0.761*CT (6.7)

Unsoaked CBR value (Predicted) = 14.316 + 1.673*C - 0.364*Rf (6.8)

Soaked CBR value (Predicted) = 13.422 + 4.074*C - 1.136*Rf (6.9)

Compression index (Predicted) = 0.484 - 0.048*C + 0.005*Rf (6.10)

Swelling pressure (predicated) = 65.042 - 6.385*C - 2.127* Rf (6.11)

Where

C = Content of cement (%)

Rf = Content of rubber fibres (%)

CT = Curing time, days

The values of relevant statistical coefficients like coefficient of multiple determination (R_2), adjusted coefficient of multiple determination ($R^2_{adjusted}$), standard error of the estimate (SE), and confidence level (CL) of maximum dry unit weight, optimum moisture content, unconfined compressive strength, split tensile strength, California Bearing Ratio value, compression index, and swelling pressure have been given in Table 6.6. The scatter plot of predicated and observed maximum dry unit weight, optimum moisture content, unconfined compressive strength, split tensile strength, California Bearing Ratio value, compression index, and swelling pressure of clayey soil mixed with cement and rubber fibres for are shown in Appendix (Fig. A73 to A78).

Fig. 6.6 Statistical coefficients of the tests

Attributes	**Statistical coefficients**			
	$\mathbf{R^2}$	$\mathbf{R^2}_{adjusted}$	**SE**	**CL (%)**
Maximum dry unit weight	0.973	0.969	0.1089	95
Optimum moisture content	0.936	0.925	0.3161	95
Unsoaked UCS	0.942	0.934	27.891	95
Soaked UCS	0.971	0.966	14.761	95
Unsoaked STS	0.897	0.885	10.030	95
Soaked STS	0.943	0.934	4.721	95
Unsoaked CBR	0.838	0.811	2.1109	95
Soaked CBR	0.961	0.954	2.2424	95
C_C	0.996	0.994	0.0058	95
Swelling pressure	0.976	0.972	3.0462	95

The coefficient of determination (R^2) of equations (6.2) to (6.11) is closure to unity. Hence the developed equations for predicting the maximum dry unit weight, optimum moisture content, unconfined compressive strength, split tensile strength, California Bearing Ratio value, compression index, and swelling pressure of clayey soil-cement-rubber fibres mixtures could be considered satisfactory.

Despite the simplicity of model, the author suggests that the model is valid within the range of cement and rubber fibres content and material tested. Beyond this range of values, the models may be checked with experimental results.

6.11 CONCLUSIONS

Based on the test results presented in this chapter, the following broad conclusions may be drawn.

6.11.1 Compaction studies

From the compaction studies, it is concluded that the maximum dry unit weight and optimum moisture content of cemented clay decreases as the content of rubber fibres in mixes increases.

6.11.2 Compression and Tension Behaviour

From the unconfined compression and tension behaviour, the following conclusion may be generally concluded.

- The incorporation of rubber fibre led to reduction of unconfined compressive strength and split tensile strength of cemented clayey soil but prosperously changes the brittle behaviour of cemented clay to ductile and reduces the rate of loss of post-peak strength. The axial and diametral deformation corresponding to peak load increases with the inclusion of rubber fibres upto 7.5%; further incorporation of rubber fibres decreases the axial and diametral deformation.
- The absolute toughness of cement-stabilized clayey soil increases with the incorporation of rubber fibres up to 7.5% for unsoaked condition. It decreases continuously in the soaked condition.
- The inclusion of rubber fibres up to 7.5% increases the toughness index of cement-stabilized clay in both compression and tension. The TI values of cement-stabilized clayey soil incorporated with rubber fibres increases with the increase in cement content.

- The absolute toughness of cement-stabilized clayey soil incorporated with rubber fibres in compression is more than tension. The TI values of cement-stabilized clayey soil incorporated with rubber fibres in compression is more than tension.
- The incorporation of rubber fibres in cemented clay decreases the stiffness and loss of post peak strength of the composite. The effect of rubber fibres in improving the post-peak response of cemented clayey soil containing rubber crumbles under tensile load is significant.
- The strain hardening and confinement effect induced by the 2.5% rubber fibres content in the cemented clay appears to be overshadowed by cementation effect. The rubberized cement stabilized clay specimens fail at relatively higher axial strain as compared to the cement stabilized clay specimens. The maximum strain corresponding to peak stress is found for cemented clay specimens containing 7.5% rubber fibres.
- The compressive axial load, tensile load, compressive axial deformation, diametral deformation, unconfined compressive strength, tensile strength, absolute toughness and toughness index in compression and tension of the clayey soil-cement-rubber fibres increased with the increase in curing period.
- The inclusion of rubber fibres promotes the formation of multiple crack/staggered cracks and consequently prevents complete brittle failure of the composite in compression. The confinement and “bridge” effect of fibres can efficiently impede the further development of tension cracks and deformation of the specimen**.**
- Due to soaking, a significant loss in the unconfined compressive strength and split tensile strength is observed.

6.11.3 California bearing ratio value

A decrease in soaked CBR values of clayey soil-cement-rubber fibre mixtures was observed with the increase in rubber fibres content.

6.11.4 One-dimensional consolidation

The compression index (Cc) of cemented clay-rubber fibres composite is lower than clay. The compression index (Cc) of cemented clayey soil increases with the increase in rubber fibres content.

6.11.5 Swelling pressure

From the Swelling pressure studies, it is concluded that the swelling pressure of clayey soil-cement-rubber fibres mixtures decreases as the content of cement and rubber fibres increases.

6.11.6 Durability Behaviour

From the durability behaviour, the following may be generally concluded.

- A decrease in the weight loss of clayey soil-cement-rubber fibres mixtures was observed with the increase in curing period.
- The weight loss of clayey soil-cement-rubber fibres mixtures increased with the increase in rubber fibres content.

6.11.7 Morphological studies

From the morphology studies, the following may be generally concluded.

- Micro-structural analysis shows that gaps are present between the rubber fibre and cemented clayey soil paste indicating weak interfaces leading to the reduced strength

6.11.8 Statistical analysis

The predicated values of maximum dry unit weight, optimum moisture content, unconfined compressive strength, split tensile strength, California Bearing Ratio value, compression index, and swelling pressure of clayey soil-cement-rubber fibres mixtures are closely matching with the observed values.

CHAPTER 7

COMPARATIVE STUDY ON THE EFFECT OF WASTE RUBBER CRUMBLES AND FIBRES INCLUSION ON THE GEOTECHNICAL PROPERTIES OF CLAYEY SOIL STABILIZED WITH CEMENT

7.1 GENERAL

This chapter focuses on the comparison of results of modified proctor compaction, unconfined compression strength, split tensile strength, California Bearing Ratio, one-dimensional consolidation, swelling pressure, wet/dry durability, and microscopic tests of uncemented/cemented clayey soil mixed with rubber crumbles and rubber fibres presented in Chapter 4, 5, and 6. The results of uncemented/cemented clayey soil mixed with rubber crumbles and rubber fibres have been compared with Indian standards for its application in low volume traffic roads, embankments, and lightweight backfill material for retaining wall.

7.2 COMPACTION TEST

Figs. 7.1 and 7.2 show the variation of maximum dry unit weight and optimum moisture content with rubber content for rubber crumbles and rubber fibres, respectively, for cement content varying from 0% to 6%.

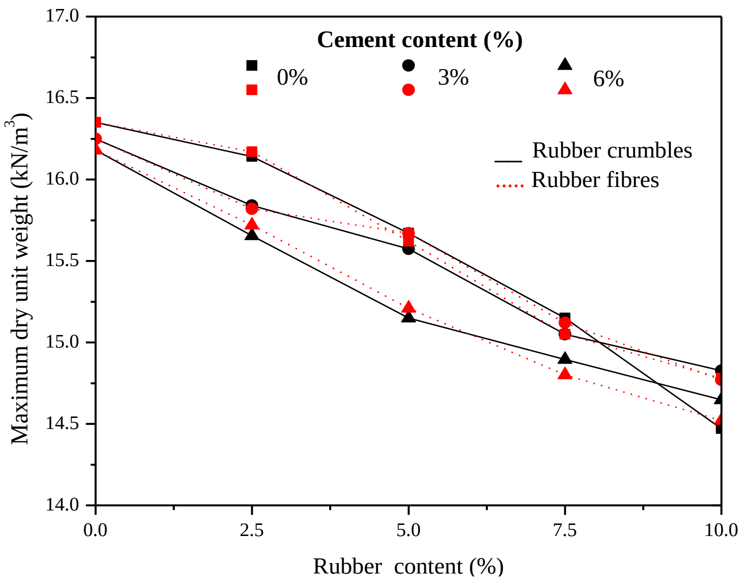


Fig. 7.1 Variation of maximum dry unit weight with rubber content for different cement contents

It is observed from Fig. 7.1 that the maximum dry unit weight of clayey soil decreases with the increase in rubber content for any percentage of cement. Fig. 7.1 reveals that the form of waste rubber (i.e. rubber crumbles or fibres) has no substantial effect on unit weight of the composite. It is also observed that in some mixtures containing specific amount of rubber fibres have slightly higher maximum dry unit weight values than those having the same amount of rubber crumbles. For example, the maximum dry unit weight of $S_{92}C_3Rc_5$ mixture was 15.6 kN/m^3, which increased to 15.7 kN/m^3 for the $S_{92}C_3Rf_5$ mixture. The possible reason of this slight difference in maximum dry unit weight is the confinement/ reinforcement effect of rubber fibres, which prevent the slippage of particles over each other during the compaction.

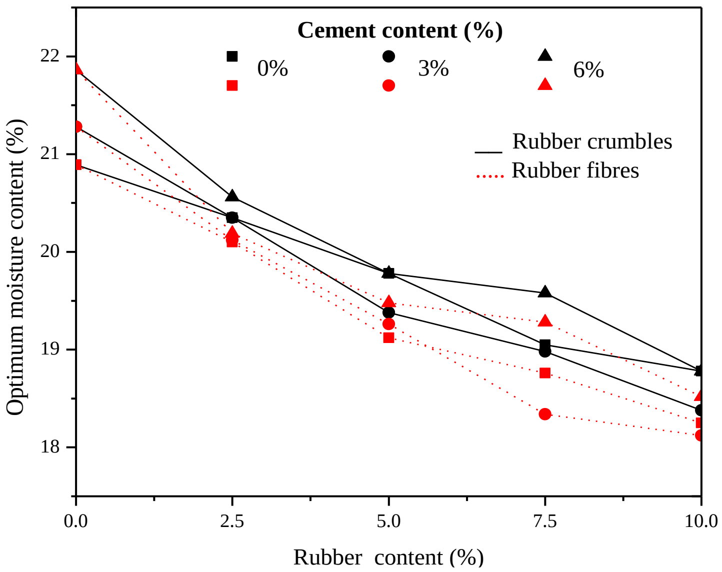


Fig. 7.2 Variation of optimum moisture content with rubber content for different cement contents

It is observed from Fig. 7.2 that adding rubber crumbles or fibres to the uncemented /cemented clayey soil causes a reduction in optimum moisture content. Rubber crumbles/fibres have negligible water absorption capacity but the specific surface area at a specific amount of rubber crumbles would be more than rubber fibres. A comparison of optimum moisture content of uncemented/cemented clayey soil incorporated with same amount of rubber crumbles and rubber fibres reveals that the optimum moisture content of mixtures incorporated with rubber crumbles is more than mixtures incorporated with rubber fibres. For example, the optimum moisture content of $S_{86.5}C_6Rf_{7.5}$ mixtures was 19.3%, which increased to 19.6% for the $S_{86.5}C_6Rc_{7.5}$ mixtures. The difference in optimum moisture content may be due to the larger specific surface area of rubber crumbles as compared to the rubber fibres at specific amount, which changes the gradation in a way that more void is created to be occupied by the water.

7.3 UNCONFINED COMPRESSION STRENGTH TEST

The variation of unconfined compression strength values with rubber content, for rubber fibres and rubber crumbles for cement content of 0%, 3%, and 6% for both unsoaked and soaked condition is shown in Figs. 7.3 and 7.4, respectively. Only the results of 28 days cured specimens of clayey soil-cement-rubber crumbles and clayey soil-cement-rubber fibres mixtures have been compared in this chapter. The results of 7 and 14 days cured specimen have been presented in Appendix (Fig. A79 to A82).

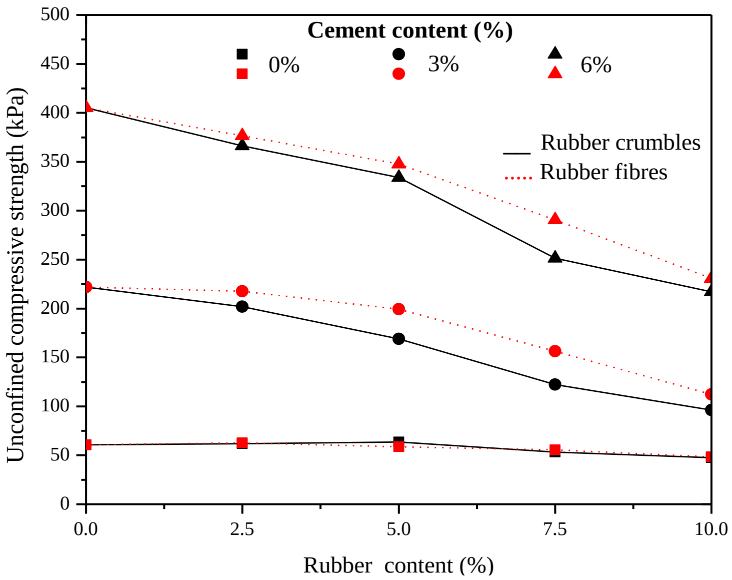


Fig. 7.3 Variation of unconfined compressive strength with rubber content for different cement contents (Unsoaked condition-28 days cured)

It is noticed from Fig. 7.3 that unconfined compressive strength of clayey soil increases marginally with the inclusion of rubber crumbles upto 5% and rubber fibres upto 2.5%. Overall, the unconfined compressive strength of clay decreases as content of rubber increases. Figs. 7.3 and 7.4 indicate that adding rubber crumbles or rubber fibres to the cemented clayey soil decreases the unconfined compression strength, and the decrease is non-linear. The unconfined compression strength of clayey soil at specific cement and rubber fibres content is more than that of clayey soil at specific cement and rubber crumbles content.

For example, the unconfined compressive strength of 28 days cured specimen $S_{89.5}C_3Rc_{7.5}$ in unsoaked condition was 251.36 kPa, which increased to 290.72 kPa for specimen $S_{86.5}C_6Rf_{7.5}$. This difference in unconfined compressive strength may possibly due to the increase reinforcement effect caused by rubber fibres in cemented clayey soil. The rate of reduction in unconfined compressive strength of cemented clay incorporated with rubber crumbles is more than rubber fibres. For example, the unconfined compressive strength of clayey soil incorporated with 6% cement reduced by 7.05%, 14.17%, 28.23% and 43.05% with inclusion 2.5%, 5%, 7.5%, and 10% rubber fibres, respectively. Whereas it reduced by 9.61%, 17.58%, 37.58%, and 46.40% with inclusion 2.5%, 5%, 7.5%, and 10% rubber crumbles respectively, at the same cement content. The reduction in rate of loss of unconfined compressive strength with the inclusion of rubber fibres in cemented clayey as compared to that of rubber crumbles may possibly due to the higher pull-out resistance of rubber fibres as compared to the rubber crumbles and thus rubber fibres have more reinforcing effect. Similar trend of reduction in strength is observed for the soaked specimens as well as shown in Fig. 7.4

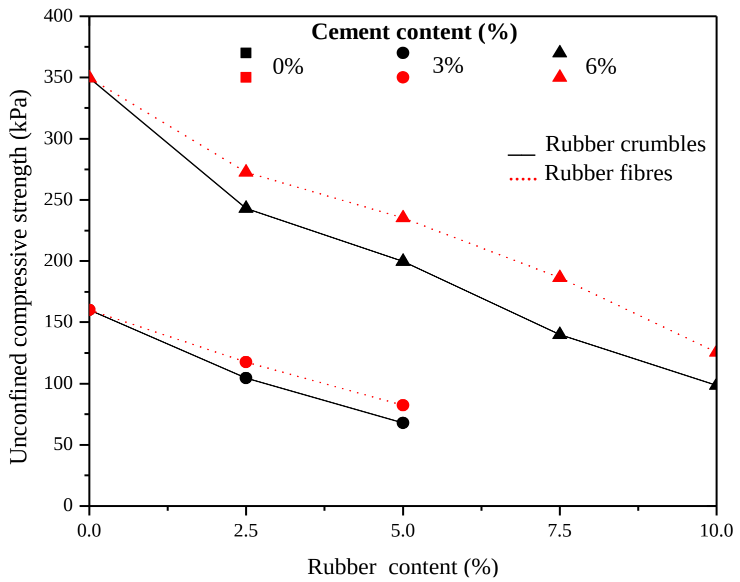


Fig. 7.4 Variation of unconfined compressive strength with rubber content for different cement contents (Soaked condition-28 days cured)

It is also observed from Fig. 7.3 that the rate of unconfined compressive strength reduction due to increase in rubber content is more at lower percentages of cement. For example, the rate of unconfined compressive strength reduction of clayey soil stabilized with 3% cement was 9.07%, 23.90%, 44.99%, and 56.67% with inclusion 2.5%, 5%, 7.5%, and 10% rubber crumbles respectively. Whereas at 6% cement content, it reduced by 9.61%, 17.58%, 37.58%, and 46.40% with inclusion 2.5%, 5%, 7.5%, and 10% rubber crumbles, respectively. By increasing the cement content, the stiffness of mixtures increases that means the mobilisation of tensile strength of rubber crumbles or fibres would be high.

Comparison of Table 5.1 and 6.1 of chapter 5 and 6 show that the absolute toughness of cement stabilized clayey soil incorporated with rubber fibres is more than cement stabilized clayey soil incorporated with rubber crumbles at any specific amount of rubber and cement content. Similarly, the value of TI of cement stabilized clayey soil incorporated with rubber fibres is more than cement stabilized clayey soil incorporated with rubber crumbles as shown in Table 5.2 and 6.2, respectively.

7.4 SPLIT TENSILE STRENGTH TEST

Figs. 7.5 and 7.6 illustrate the variation of split tensile strength with rubber content for uncemented and cemented clayey soil for unsoaked and soaked conditions, respectively. Only the results of 28 days cured specimens of clayey soil-cement-rubber crumbles and clayey soil-cement-rubber fibres mixtures have been compared in this chapter. The results of 7 and 14 days cured specimen has been presented in Appendix (Fig. A83 to A86).

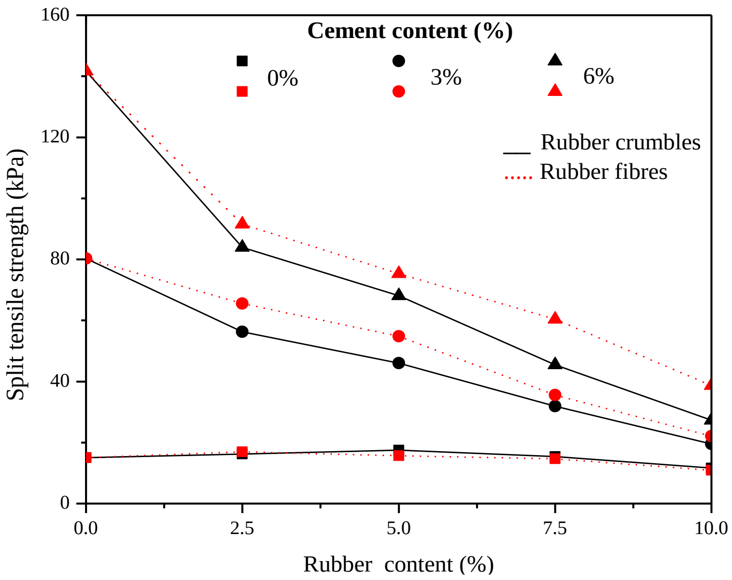


Fig. 7.5 Variation of split tensile strength with rubber content for different cement contents (Unsoaked condition-28 days cured)

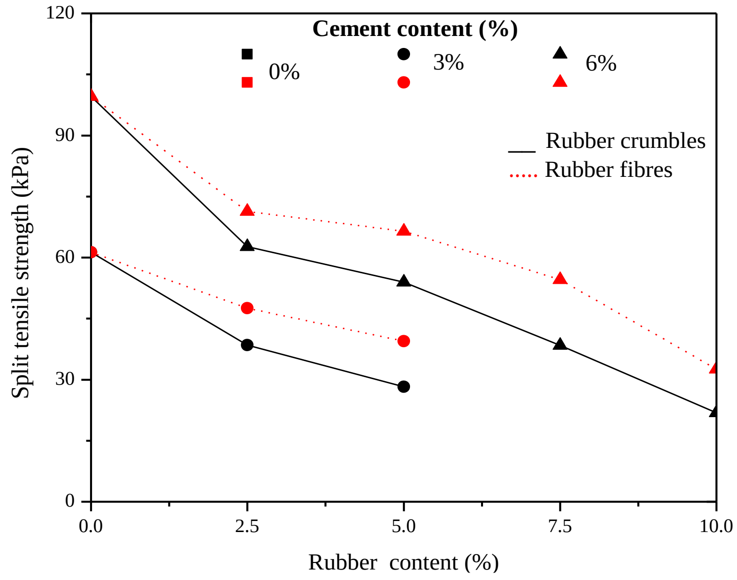


Fig. 7.6 Variation of split tensile strength with rubber content for different cement contents (soaked condition-28 days cured)

The variation of split tensile strength of cemented clayey soil incorporated with rubber crumbles and rubber fibres is in concord with the unconfined compressive strength. The split tensile strength of clayey soil at same specific cement and rubber fibres content is more than that of clayey soil at specific cement and rubber crumbles content. For example, the split tensile strength 28 days cured specimen $S_{86.5}C_6Rc_{7.5}$ in unsoaked condition was 45.44 kPa, which increased to 60.42 kPa for specimen $S_{86.5}C_6Rf_{7.5}$. The rate of reduction in split tensile strength of cemented clay incorporated with rubber crumbles and rubber fibres is similar to the unconfined compressive strength. For example, the split tensile strength of clayey soil incorporated with 6% cement reduced by 35.36%, 46.85%, 57.36%, and 71.95% with the inclusion 2.5%, 5%, 7.5%, and 10% rubber fibres, respectively. Whereas it reduced by 40.79%, 51.20%, 67.93%, and 80.29% with inclusion 2.5%, 5%, 7.5%, and 10% rubber crumbles respectively, at the same cement content. The rubber fibres show “bridge” effect, which efficiently impedes the further opening and development of tension cracks, may be responsible for the increase in split tensile strength. Similar trend of reduction in strength is observed for the soaked specimens as well indicated in Fig. 7.6.

Comparison of Table 5.3 and 6.3 of chapter 5 and 6 show that the absolute toughness of cement stabilized clayey soil incorporated with rubber fibres is more than cement stabilized clayey soil incorporated with rubber crumbles at any specific amount of rubber and cement content. The value of TI of cement stabilized clayey soil incorporated with rubber crumbles is very low and ranges between 0.05 to 0.2 as shown in Table 5.4 indicates the brittle behaviour of the composite. It shows the ineffectiveness of rubber crumbles under tensile stresses. Whereas, the value of TI of cement stabilized clayey soil incorporated with rubber fibres is higher than the cement stabilized clayey soil incorporated with rubber crumbles as shown in Table 5.4.

7.5 CALIFORNIA BEARING RATIO TEST

Figs. 7.7 and 7.8 show the California Bearing Ratio values of clayey soil incorporated with different percentages of cement, rubber crumbles and rubber fibres for both unsoaked and soaked conditions, respectively. It can be inferred from Fig. 7.7 that California Bearing Ratio value of clayey soil incorporated with 5% rubber crumbles and 2.5% rubber fibres is almost similar. Beyond 5% and 2.5% of rubber crumbles and rubber fibres doses, the California Bearing Ratio value of clayey soil decreases in the unsoaked condition. Whereas, a continuous reduction in California Bearing Ratio values is observed for the soaked condition as shown in Fig. 7.8. The rate of reduction of California Bearing Ratio value for both clayey soils incorporated with rubber crumbles and rubber fibres is almost same. The inclusion of cement in clayey soil incorporated with rubber crumbles and rubber fibres increased the California Bearing Ratio value as shown in Fig. 7.7. Although, it decreases as the rubber content is increased. The rate of reduction in California Bearing Ratio value is approximately same.

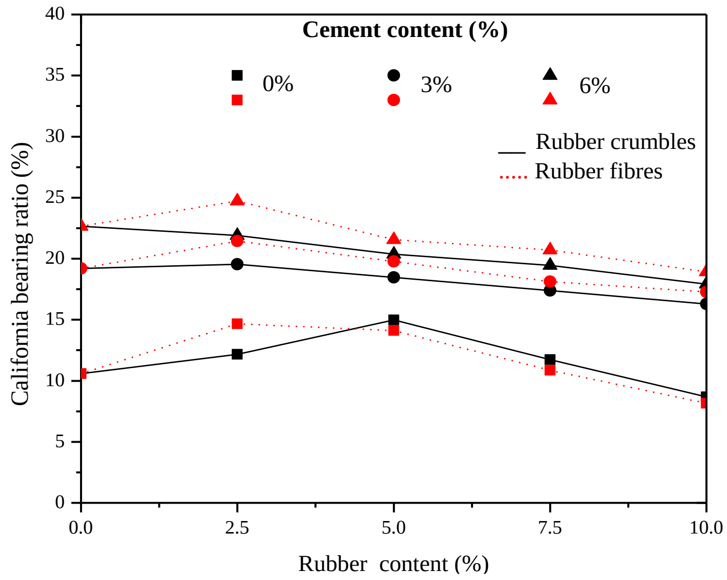


Fig. 7.7 Variation of California Bearing Ratio with rubber content for different cement contents (Unsoaked condition)

The soaked California Bearing Ratio values of cemented clay incorporated with specific amount of rubber fibres is more than the cemented clay incorporated with rubber crumbles. For example, the soaked California Bearing Ratio of clayey soil stabilized with 6% cement was 34.56%, 31.56%, 28.32%, and 24.56% with the inclusion of 2.5%, 5%, 7.5%, and 10% rubber fibres, respectively. Whereas it was 32.04%, 27.52%, 25.52% and 22.81% with the inclusion of 2.5%, 5%, 7.5%, and 10% rubber crumbles, respectively at the same cement content. The rate of reduction in California Bearing Ratio of cemented clay incorporated with rubber fibres is less than rubber crumbles. For example, the California Bearing Ratio values of clayey soil incorporated with 6% cement reduced by 16.90%, 28.63%, 32.46%, and 40.68% with inclusion 2.5%, 5%, 7.5%, and 10% rubber crumbles, respectively. Whereas it reduced by 10.30%, 18.12%, 26.58%, and 36.30% with inclusion 2.5%, 5%, 7.5%, and 10% rubber fibres respectively, at the same cement content. The lesser void ratio of cemented clayey soil incorporated with rubber fibres and mobilization of tensile strength in the extensible rubber fibres, which offers higher resistance to penetration in comparison of cemented clayey soil incorporated with rubber crumbles, may be possible reasons for such differences.

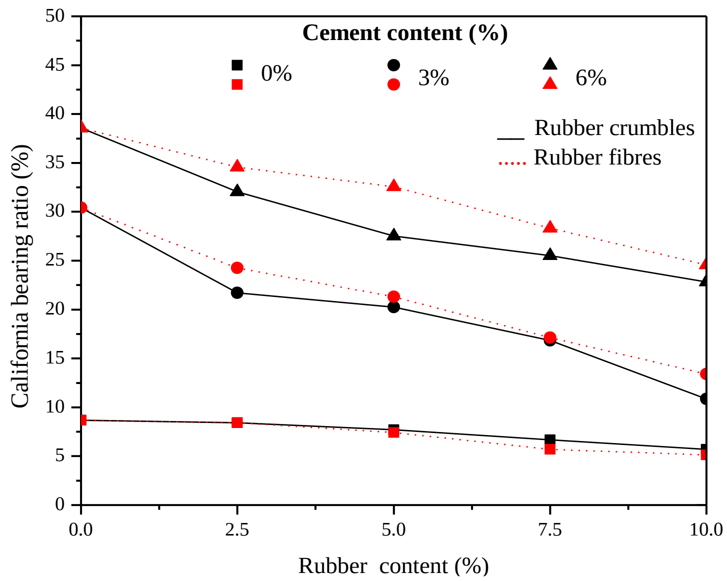


Fig. 7.8 Variation of California Bearing Ratio with rubber content for different cement contents (Soaked condition)

7.6 ONE-DIMENSIONAL CONSOLIDATION TEST

Fig. 7.9 presents the effect of rubber content on compression index (C_C) values of uncemented/cemented clayey soil containing both rubber crumbles and rubber fibres. It can be observed from Fig. 7.9 that the C_C values of the clayey soil increased with the increase in rubber content for both rubber crumbles and rubber fibres. Similarly, the compression index value of cement-rubber crumbles-treated clayey soils and cement-rubber fibres-treated clayey soils increases with the increasing rubber content as evident in Fig. 7.9. The increase in C_C values could be attributed to the increased void ratio resulting from the addition of rubber particles and compression of these voids resulted in higher C_C values. The rate of increment of C_C values of clayey soil-cement-rubber fibres mixtures is less than the clayey soil-cement-rubber fibres mixtures. For example, the of clayey soil- rubber fibres mixtures stabilized with 6% cement shows 4.61%, 15.10%, 20.31%, and 29.68% increment in the C_C values with the inclusion of 2.5%, 5%, 7.5%, and 10% rubber fibres content, respectively. Similarly, the of clayey soil- rubber crumbles mixtures stabilized with 6% cement shows 7.81%, 20.31%, 33.33%, and 43.75% increment in the C_C values with the inclusion of 2.5%, 5%, 7.5%, and 10% rubber crumbles content, respectively.

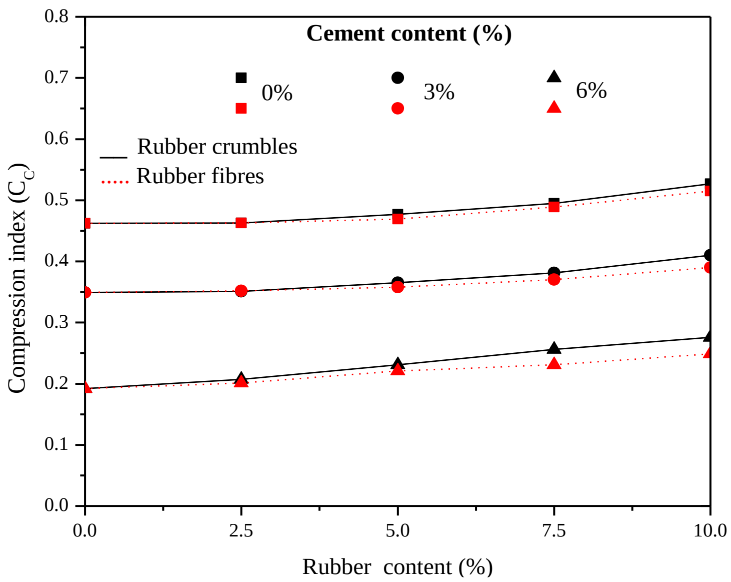


Fig. 7.9 Variation of compression index (C_C) with rubber content for different cement contents

The rubber particles have relatively low compressibility as compared to clayey soil particles. When the clayey soil-cement-rubber crumbles/fibres specimens were subjected to load increments, the inequality in compressibility of rubber particles and rest of composite have created voids in the mixtures. The lower rate of increment of C_C values of cemented clayey soil incorporated with rubber fibres could be attributed to the binding effect of rubber fibres, which restricts the movement of cemented clayey particles much better than rubber crumbles. Therefore, the rubber fibres have better performance then rubber crumbles.

7.7 SWELLING PRESSURE TEST

Fig. 7.10 reveals the variation of swelling pressure of clayey soil with rubber content for rubber crumbles and rubber fibres, respectively, for cement content varying from 0% to 6%. As the content of rubber in the uncemented/cemented clayey soil increases, the swelling pressure gradually decreases as expected as shown in Fig. 7.10. The reduction in swelling pressure of uncemented/cemented clayey soil incorporated with rubber fibres is more than rubber crumbles. In the case of clayey soil stabilized with 6% cement, increasing the rubber fibres content from 2.5% to 10% promoted a noticeable reduction of 29.34% to 68.54% in swelling pressure. Similarly, in case of clayey soil stabilized with 6% cement, increasing the rubber crumbles content from 2.5% to 10% promoted a reduction of 23.51% to 52.23% in swelling pressure. The reduction in swelling pressure of composite depends upon the replacement of swelling clayey soil particles by completely non-swelling rubber particles, appearance of resistive tension forces among rubber particles, and voids in the composite, which creates a drainage path for the dissipation of pore water. The reduction in swelling pressure depends on the net magnitude of entire factors. The possible reason of higher reduction in swelling pressure of uncemented/cemented clayey incorporated with rubber fibres as compared to the uncemented/cemented clayey incorporated with rubber crumbles is the greater net magnitude of the factors mention above. The reinforcement effect induced by rubber fibres in uncemented/cemented clayey able to encounter the tensile stress induced due to the swelling of clayey particles. Therefore, rubber fibres can prevent the occurrence of swelling with much more efficiency compared to rubber crumbles.

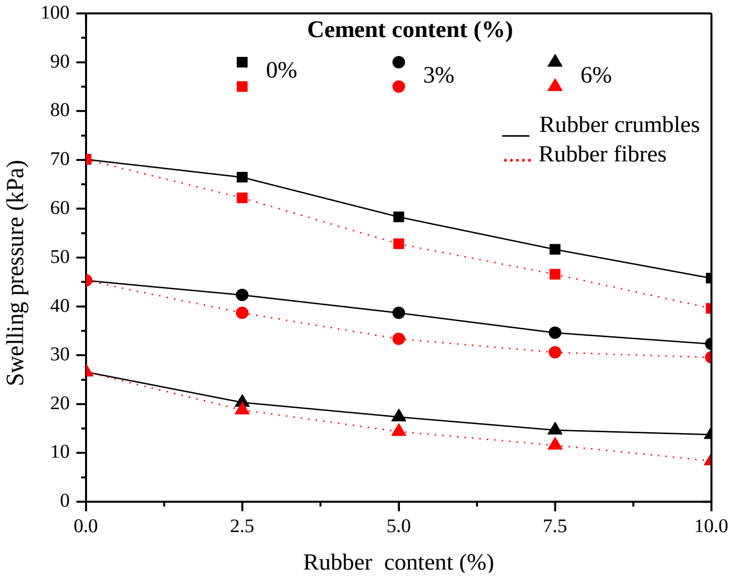


Fig. 7.10 Variation of swelling pressure with rubber content for different cement contents

7.8 WET/DRY DURABILITY TEST

The variation of weight loss of 180 days cured specimens of clayey soil-cement-rubber crumbles/fibres with rubber content after completion of 12 wet-dry cycles are shown in Fig. 7.11. It can be seen from Fig. 7.11 that the weight loss of clayey soil-cement-rubber crumbles/fibres increases with the increase in rubber content. The rate of increment of weight loss of clayey soil-cement-rubber crumbles specimens is more than in case of the clayey soil-cement-rubber fibres specimens. The greater void ratio of specimens incorporated with rubber crumbles as compared to the specimens incorporated with rubber fibres and reinforcement effect generated by rubber fibres may be responsible for the better performance of clayey soil-cement-rubber fibres specimens over the clayey soil-cement-rubber crumbles specimens.

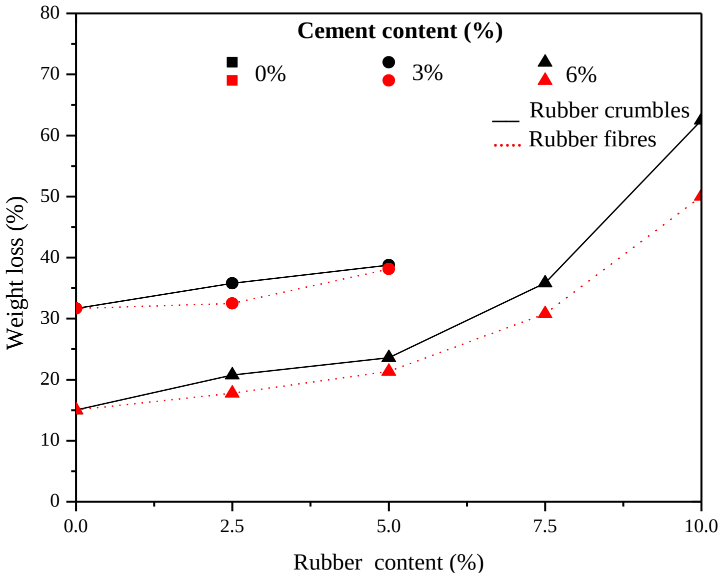


Fig. 7.11 Variation of weight loss with rubber content for different cement contents (180 days cured)

7.9 APPLICATIONS

A significant increase in the construction activities such as highways, railways, airports, embankments, abutments and earthen dams has been seen to fulfil the social and economical need of the enlarging population across the globe. This sudden increase in population accompanied with uplift in living standard consequently has resulted in the depletion of suitable land for construction activities, particularly in metropolitan cities. The only possible solution to this serious problem is the improvement in the geotechnical properties of existing soil.

The potential utilization of waste tire is nowadays has become a major challenge in front of the engineering community because of its deteriorating impact on the quality of environment. About 1.5 billion tires are manufactured in the world per annum and 1000million tires reach the cessation of their subsidiary life every year. This number can gain up to 1200 million tires per year, by the year 2030. In Indian scenario, 112 million discarded tires generated per year. These discarded tires are disposed to either landfills, stockpiled or burn off, which causes serious health and ecological problems. The recycling and reuse of these discarded waste tires can only minimize its environmental impacts.

With this reason, Indian government is encouraging the use of waste materials. IRC: SP-20-(2002) - Indian Road Congress Special Publication has also recommended the use of waste materials in the low volume road construction. On the other hand, due to the scarcity of traditional fill material, there is need to develop new lightweight backfill material for retaining walls. This section describes the application of clayey soil-cement-rubber crumbles and clayey soil-cement-rubber fibres mixtures. The results of the composite have been compared with various Indian standards as well.

The main criterion of fill material selection is the unit weight and draining properties. According to the MORD 2014 (Ministry of Rural Development: Specification of Rural Roads Published by Indian Road Congress 2014), Table 300-1, the density of embankment should be:

Table 7.1 Density requirements for Embankment

Sl.No	Type of work	Maximum laboratory dry unit weight when tested as per IS: 2720 (Part 8)
1.	Embankments up to 3 metres height, not subjected to extensive flooding	Not less than 15.2 kN/cu.m
2.	Embankments exceeding 3 metres height or embankments of any height subject to long periods of inundation	Not less than 16.0 kN/cu.m

Notes: (1) This Table is not applicable for lightweight fill material e.g. cinder, fly ash etc.
(2) The Engineer may relax these requirements at his discretion taking into account the availability of materials for construction and other relevant factors.

Table 7.2 Density requirements for embankment (For rural roads)

Sl.No	Type of work	Maximum laboratory dry unit weight when tested as per IS: 2720 (Part 8)
1.	Embankments up to 3 metres height, not subjected to extensive flooding	Not less than 14.4 kN/cu.m
2.	Embankments exceeding 3 metres height or embankments of any height subject to long periods of inundation	Not less than 15.2 kN/cu.m

The unit weight of proposed composite lies between 16.35 kN/m^{3}to 14.47 kN/m^3. The unit weight of the various combination of uncemented/cemented clayey soil incorporated with rubber crumbles/fibres has been compared with these clauses mentioned in Table 7.1 and 7.2 and shown in Table 7.3 and Table 7.4 for its application in embankment construction for rural roads. The combinations, which satisfy the criteria, have been shown by symbol "✓".The combinations, which not satisfy the criteria, have been shown by symbol "x".

Table 7.3 and Table 7.4 show that all combinations of uncemented/cemented clayey soil incorporated with rubber crumbles and rubber fibres satisfy the criteria of unit weight for the utilization of proposed composite in the construction of embankments of up to 3 meters height, which is not subjected to extensive flooding. For the embankment of height more than 3 meters, the rubber content in the mixture should not be more than 5%. A comparison of unit weight between composite obtained from the incorporation of cement and rubber crumbles/fibres in clayey soil and clayey soil alone reveals that reduction of unit weight could give a surplus benefit to the composite when it would be used as fill material and backfilling material for retaining wall as well. The leachate and drainage study of the proposed composite is beyond the scope of present research.

Table 7.3 Comparison of unit weight of clayey soil-cement-rubber crumbles mixture with MORD, 2014

Mix Designation	**Maximum dry unit weight (kN/m^3)**	**Density requirements for embankment (For rural roads)**	
		Embankments up to 3 metres height, not subjected to extensive flooding	**Embankments exceeding 3 metres height or embankments of any height subject to long periods of inundation**
		Not less than 14.4 kN/cu.m	Not less than 15.2 kN/cu.m
S_{ref}	16.35	✓	✓
$S_{97.5}C_0Rc_{2.5}$	16.14	✓	✓
$S_{95}C_0Rc_5$	15.67	✓	✓
$S_{92.5}C_0Rc_{7.5}$	15.15	✓	x
$S_{90}C_0Rc_{10}$	14.47	✓	x
$S_{97}C_3Rc_0$	16.25	✓	✓
$S_{94}C_6Rc_0$	16.18	✓	✓
$S_{94.5}C_3Rc_{2.5}$	15.84	✓	✓
$S_{92}C_3Rc_5$	15.57	✓	✓
$S_{89.5}C_3Rc_{7.5}$	15.05	✓	x
$S_{87}C_3Rc_{10}$	14.82	✓	x
$S_{91.5}C_6Rc_{2.5}$	15.65	✓	✓
$S_{89}C_6Rc_5$	15.15	✓	x
$S_{86.5}C_6Rc_{7.5}$	14.89	✓	x
$S_{84}C_6Rc_{10}$	14.64	✓	x

✓: Satisfied; X: Unsatisfied

Table 7.4 Comparison of unit weight of clayey soil-cement-rubber fibres mixture with MORD, 2014

Mix Designation	Maximum dry unit weight (kN/m^3)	Density requirements for embankment (For rural roads)	
		Embankments up to 3 metres height, not subjected to extensive flooding	**Embankments exceeding 3 metres height or embankments of any height subject to long periods of inundation**
		Not less than 14.4 kN/cu.m	Not less than 15.2 kN/cu.m
$S_{97.5}C_0Rf_{2.5}$	16.17	✓	✓
$S_{95}C_0Rf_5$	15.62	✓	✓
$S_{92.5}C_0Rf_{7.5}$	15.05	✓	x
$S_{90}C_0Rf_{10}$	14.78	✓	x
$S_{94.5}C_3Rf_{2.5}$	15.82	✓	✓
$S_{92}C_3Rf_5$	15.67	✓	✓
$S_{89.5}C_3Rf_{7.5}$	15.12	✓	x
$S_{87}C_3Rf_{10}$	14.77	✓	x
$S_{91.5}C_6Rf_{2.5}$	15.72	✓	✓
$S_{89}C_6Rf_5$	15.20	✓	✓
$S_{86.5}C_6Rf_{7.5}$	14.80	✓	x
$S_{84}C_6Rf_{10}$	14.52	✓	x

✓: Satisfied; X: Unsatisfied

According to MORD 2014 Clause 401.2.2 (Ministry of Rural Development: Specification of Rural Roads Published by Indian Road Congress 2014), the sub-base material in soaked condition should have minimum 20% CBR value. According to IRC 20: 2002 (Rural Roads Manual Published by the Indian Roads Congress) when the CBR of subgrade is less than 2 per cent a capping layer of 100 mm thickness of material with a minimum CBR of 10 per cent is to be provided in addition to the sub-base required for CBR of 2 percent. If the subgrade CBR is more than 15 per cent, there is no need to provide a sub-base. The sub-base material should have minimum soaked CBR of 15 percent. The soaked CBR value of clay (without and with rubber crumbles/fibres) has found less than 10%. The soaked CBR values of cement-stabilized soil containing rubber crumbles/fibres mixtures have been found more than the requirements of Indian standard for all percentages of cement and rubber crumbles/fibres inclusion as illustrated in Table 7.5 and Table 7.6 except mixture $S_{89.5}C_3Rc_{7.5}$and $S_{87}C_3Rc_{10}$.

Table 7.5 Comparison of California Bearing Ratio of clayey soil-cement-rubber crumbles mixtures with various Indian standards

Mix Designation	Soaked CBR Value(%)	Various clauses of Indian standards		
		MORD 2014 (sub base) min. 20%	**IRC 20: 2002 (sub grade) min. 10%**	**IRC 20: 2002 (sub base) min. 15%**
S_{ref}	8.69	x	x	x
$S_{97.5}C_0Rc_{2.5}$	8.42	x	x	x
$S_{95}C_0Rc_5$	7.70	x	x	x
$S_{92.5}C_0Rc_{7.5}$	6.68	x	x	x
$S_{90}C_0Rc_{10}$	5.70	x	x	x
$S_{97}C_3Rc_0$	30.41	✓	✓	✓
$S_{94}C_6Rc_0$	38.56	✓	✓	✓
$S_{94.5}C_3Rc_{2.5}$	21.72	✓	✓	✓
$S_{92}C_3Rc_5$	20.26	✓	✓	✓
$S_{89.5}C_3Rc_{7.5}$	16.84	x	✓	✓
$S_{87}C_3Rc_{10}$	10.86	x	✓	x
$S_{91.5}C_6Rc_{2.5}$	32.56	✓	✓	✓
$S_{89}C_6Rc_5$	27.52	✓	✓	✓
$S_{86.5}C_6Rc_{7.5}$	25.52	✓	✓	✓
$S_{84}C_6Rc_{10}$	22.81	✓	✓	✓

✓: Satisfied; X: Unsatisfied

Table 7.6 Comparison of California Bearing Ratio of clayey soil-cement-rubber fibres mixtures with various Indian standards

Mix Designation	Soaked CBR Value(%)	Various clauses of Indian standards		
		MORD 2014 (sub base) min. 20%	IRC 20: 2002 (sub grade) min. 10%	IRC 20: 2002 (sub base) min. 15%
$S_{97.5}C_0Rf_{2.5}$	8.42	x	x	x
$S_{95}C_0Rf_5$	7.42	x	x	x
$S_{92.5}C_0Rf_{7.5}$	5.70	x	x	x
$S_{90}C_0Rf_{10}$	5.13	x	x	x
$S_{94.5}C_3Rf_{2.5}$	24.25	✓	✓	✓
$S_{92}C_3Rf_5$	21.32	✓	✓	✓
$S_{89.5}C_3Rf_{7.5}$	17.12	x	✓	✓
$S_{87}C_3Rf_{10}$	13.41	x	✓	x
$S_{91.5}C_6Rf_{2.5}$	34.56	✓	✓	✓
$S_{89}C_6Rf_5$	31.57	✓	✓	✓
$S_{86.5}C_6Rf_{7.5}$	28.32	✓	✓	✓
$S_{84}C_6Rf_{10}$	24.56	✓	✓	✓

✓: Satisfied; X: Unsatisfied

According to IS : 9451-1994, the maximum swelling pressure exerted by expansive soil on the side slope and bed of canal in cutting or embankment should be range between 50 to 300 kN/m^2. For cohesive non-swelling soils containing illite and kaolinite and their combination minerals, it should not be more than 10 kN/m^2. The swelling pressure exerted by the clayey soil on the structure is considered negligible if it is less than 20 kN/m^2. Portland Cement Association (PCA) has recommended that the weight loss of granular soils of low plasticity and cohesive clays should not be more 14% and 7% respectively, after completion of 12 wet and dry cycles. According to some other studies, these recommendations were found to stringent. According to the IRC: SP: 89-2010, section 4.7.2, the weight loss of material to be used for the construction of base, sub-base and shoulder should not be more than 20%, 30%, and 30%, respectively. The values of the swelling pressure and weight loss of the composite has been compared with the requirement of Indian standard as shown in Table 7.7 and Table 7.8.

Table 7.7 Comparison of the swelling pressure and durability test results of clayey soil-cement-rubber crumbles mixtures with codal provisions

Test	Swelling pressure	Durability	
	Criteria		
Sample no	Should not be more than 20 kN/m^2	Weight loss for base should not be more than 20%	Weight loss for sub base should not be more than 30%
S_{ref}	x	x	x
$S_{97.5}C_0Rc_{2.5}$	x	x	x
$S_{95}C_0Rc_5$	x	x	x
$S_{92.5}C_0Rc_{7.5}$	x	x	x
$S_{90}C_0Rc_{10}$	x	x	x
$S_{97}C_3Rc_0$	x	x	x
$S_{94}C_6Rc_0$	x	✓	✓
$S_{94.5}C_3Rc_{2.5}$	x	x	x
$S_{92}C_3Rc_5$	x	x	x
$S_{89.5}C_3Rc_{7.5}$	x	x	x
$S_{87}C_3Rc_{10}$	x	x	x
$S_{91.5}C_6Rc_{2.5}$	x	x	✓
$S_{89}C_6Rc_5$	✓	x	✓
$S_{86.5}C_6Rc_{7.5}$	✓	x	x
$S_{84}C_6Rc_{10}$	✓	x	x

✓: Satisfied; X: Unsatisfied

Table 7.7 shows that only the mixtures $S_{89}C_6Rc_5$, $S_{86.5}C_6Rc_{7.5}$, and $S_{84}C_6Rc_{10}$ satisfies the criteria of swelling pressure for the utilization of proposed composite in the construction of side slope of the canal. The clayey soil incorporated with 6% cement and rubber fibres up to 7.5% fulfils the requirement of Indian standards related to the utilization of proposed composite for the lining of canals as shown in Table 7.8.

Table 7.8 Comparison of the swelling pressure and durability test results of clayey soil-cement-rubber fibres mixtures with codal provisions

Test	**Swelling pressure**	**Durability**	
	Criteria		
Sample no	**Should not be more than 20 kN/m²**	**Weight loss for base should not be more than 20%**	**Weight loss for sub base should not be more than 30%**
$S_{97.5}C_0Rf_{2.5}$	x	x	x
$S_{95}C_0Rf_5$	x	x	x
$S_{92.5}C_0Rf_{7.5}$	x	x	x
$S_{90}C_0Rf_{10}$	x	x	x
$S_{94.5}C_3Rf_{2.5}$	x	x	x
$S_{92}C_3Rf_5$	x	x	x
$S_{89.5}C_3Rf_{7.5}$	x	x	x
$S_{87}C_3Rf_{10}$	x	x	x
$S_{91.5}C_6Rf_{2.5}$	✓	✓	✓
$S_{89}C_6Rf_5$	✓	x	✓
$S_{86.5}C_6Rf_{7.5}$	✓	x	✓
$S_{84}C_6Rf_{10}$	✓	x	x

✓: Satisfied; X: Unsatisfied

Over all from these results, the maximum percentage of rubber crumbles and rubber fibres content that can be incorporated in cement stabilized clayey soil should not be more than 5% and 7.5% respectively. The incorporation of rubber crumbles and fibres in cemented clay would not just only improve the geotechnical properties but open a substantially new venue for its disposal with subsequent health and environmental benefits. The huge quantity of this hazardous waste can be utilized for construction of voluminous structures like roads having low traffic intensity, lightweight backfill behind retaining wall, etc. Its use in clay will be intensely profitable in consideration of vision for the sustainable environment and development.

7.10 COST ANALYSIS

Table 7.9 shows the comparative cost analysis performed for the stabilization of an assumed area of 10m x 10m treated up to 1m depth by using rubber crumbles, rubber fibres, polypropylene fibres, and steel fibres as reinforcement. The costs of rubber crumbles, rubber fibres, propylene fibres and steel fibres are taken as Rs. 10/kg, Rs. 16/kg, Rs. 618/kg and Rs. 170/kg respectively as per the prevailing market rates. Here, only three materials have been compared for the sake of convenience. This analysis shows significant benefit (cost) of using rubber crumbles and fibres as reinforcement material over polypropylene fibres and steel fibres. However, cost analysis considers material costs alone. Other costs including excavation costs, hauling costs, soil-mixing costs, compaction costs, labour costs and costs of other additives (cement/lime) are required to obtain a total cost of the work. Estimated cost per kg for different reinforcement materials was calculated by using the optimum dose as suggested by the researchers in their work.

Table 7.9 Cost comparison[a]

Reinforcement material	**Dose (%)**	**Quantity (kg)**	**Unit price (Rs.) per kg**	**Total cost (Rs.) (approx.)**
Rubber crumbles	5%	1668.36	16	26,693
Rubber fibres	7.5%	2502.55	10	25,020
Polypropylene Fibre*	0.5%	166.835	618	1,03,104
Steel Fibre*	10%	3336.70	170	5,67,239
Polypropylene Fibre[+]	0.25%	83.41	618	51,547

[a]Unit prices base upon tentative market rate in India (2016)

* Suggested by Fatahi et al. (2012)

[+]Suggested by Tang et al. (2007)

Assuming the performance of rubber crumbles, rubber fibres, polypropylene fibres and steel fibres relatively equal, and considering the fact that rubber crumbles/fibres could be used at very low cost as compared to other reinforcement materials, utilization of rubber crumbles/fibres for reinforcement appears to be a logical choice. The disposal/utilization of waste tire incorporation with clay would not be only economical but also mitigate the detrimental effect of this inexpedient waste on health, environment and ecological systems.

7.11 CONCLUSIONS

Based on the test results presented in this chapter, the following broad conclusions may be drawn.

- The addition of rubber crumbles/fibres to clayey soil and clayey soil-cement mixtures decreases the maximum dry unit weight; the decrease is slightly more with the inclusion of rubber crumbles compared to rubber fibres. Similarly, the optimum moisture content of the mixtures decreases as the content of rubber crumbles/fibres increases. The optimum moisture content of clayey soil and clayey soil-cement mixtures incorporated with rubber fibres is less as compared to the same mixtures incorporated with rubber crumbles.
- Addition of rubber crumbles and fibres up to 5% and 2.5%, respectively improves the unconfined compressive strength and split tensile strength of clayey soil marginally. Further inclusion of rubber crumbles/fibres reduces the strength. Adding rubber crumbles and rubber fibres to clayey soil-cement mixtures reduce the unconfined compressive strength and split tensile strength. The rate of reduction in strength with inclusion of rubber crumbles is more than rubber fibres. The soaked specimens of clayey soil-cement mixture incorporated with rubber crumbles and rubber fibres show similar results as well.
- The California Bearing Ratio values for soaked condition of clayey soil and clayey soil-cement mixtures decreases as the content of rubber crumbles and rubber fibres increases. The use of rubber fibres in cemented clayey soil results in better outcomes in terms of reduction in rate of loss of California Bearing Ratio values as compared to rubber crumbles.
- Adding rubber crumbles and rubber fibres to uncemented/cemented clayey soil mixtures increases the compression index. Rubber fibres perform better than the rubber crumbles in reducing the rate of increase in compression index of mixtures.
- The swelling pressure of uncemented/cemented clayey soil mixtures incorporated with rubber crumbles and rubber fibres decreases as the rubber content increases. The inclusion of rubber fibres in cemented clayey soil has decreased the swelling pressure more as compared to rubber crumbles.
- The weight loss of cemented clayey soil incorporated with rubber crumbles mixtures are more than cemented clayey soil incorporated with rubber fibres.

7.11.1 Applications

From the application point of view of this composite material, following are the conclusions and recommendations:

- The cemented clayey soil mixed with 2.5% to 10% rubber crumbles and rubber fibres have satisfied the required criteria of density for embankment construction of height 3 m (max.) for rural roads, which is not subjected to extensive flooding. The uncemented clayey soil mixed with rubber crumbles and rubber fibres up to 5% have satisfied the density requirement for embankment (for rural roads) of height more than 3 meters. The clayey soil stabilized with 3% cement incorporated with 2.5% to 5% rubber crumbles and 2.5% to 5% rubber fibres have satisfied this criterion. Similarly, the clayey soil stabilized with 6% cement incorporated with 2.5% rubber crumbles and 2.5% to 5% rubber fibres have satisfied this criterion.
- The soaked California Bearing Ratio values of clayey soil incorporated with rubber crumbles and fibres is less than 10%. Therefore, the pre-requisite treatment of clayey soil incorporated with rubber crumbles and fibres is needed for its application in sub grade and sub base. The soaked California Bearing Ratio values of clayey soil stabilized with 3% cement containing 2.5% to 7.5% rubber crumbles and rubber fibres have satisfied all the criteria of various codal provisions for its application in sub grade and sub base course. Whereas, the soaked California Bearing Ratio values of 6% cement stabilized clayey soil incorporated with rubber crumbles and rubber fibres have been found more than the requirements of Indian standards for all percentage of rubber content.
- The clayey soil-cement-rubber crumbles and clayey soil-cement-rubber fibres mixtures containing 3% cement do not satisfy the codal provisions for its application in slide slope of canal. The clayey soil mixed with 6% cement and 5% to 10% rubber crumbles have swelling pressure less than 20%. Similarly, the swelling pressure of clayey soil stabilized with 6% cement containing 2.5% to 10% rubber fibres have satisfied the criteria of maximum swelling pressure.
- The durability of clayey soil mixed with rubber crumbles and rubber fibres is questionable. The clayey soil treated with 3% cement, 2.5% to 10% rubber crumbles, and rubber fibres do not satisfy the criteria of weight loss for its application in base courses and sub base courses of pavements. The optimum dose of rubber fibres in the clayey soil stabilized with 6% cement is 2.5% for its application in base course of road pavement. Similarly, the rubber crumbles and rubber fibres up to 5% and 7.5% respectively could be incorporated successfully in clayey soils stabilized with 6% cement for its application in sub base course of road pavements.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1 GENERAL

In the present work, detailed experimental studies were carried out on utilization of waste rubber tyre in uncemented and cemented clayey soil. Two forms of waste rubber (i) crumbles and (ii) rubber fibres were used in this study. For this study, three percentages of cement (0%, 3% and 6%) and five percentages of rubber crumbles and rubber fibres were considered. The tests namely, compaction, unconfined compressive strength, split tensile strength, California Bearing Ratio, one dimensional consolidation, swelling pressure, and wet/dry cycles durability along with the XRD and SEM were conducted on clayey soil-cement-rubber crumbles/fibres mixtures to ascertain the suitability of rubber crumbles/fibres with cement stabilized clayey soil.

Following are the important conclusions of the study:

1. Incorporation of rubber crumbles and rubber fibres beyond 10% is not practically possible because of the poor bonding between clayey soil and rubber particles, and accumulation of rubber particles at higher content.

2. From the modified proctor test conducted on clayey soil with and without cement and rubber crumbles/fibres, it was observed that the maximum dry unit weight and optimum moisture content of clayey soil with and without cement decreased as the content of rubber crumbles/fibres increased. Whereas, increase in the percentage of cement in clayey soil incorporated with rubber crumbles/fibres resulted into decrement in maximum dry unit weight and increment in optimum moisture content.

3. In the unconfined compressive strength and split tensile strength test, a marginal improvement in strength of clayey soil incorporated with rubber crumbles and rubber fibres upto 5% and 2.5% was noticed. As the amount of rubber crumbles and rubber fibres was increased beyond 5% and 2.5%, a reduction in strength was observed. Similarly, an increase in the absolute toughness and toughness index was noticed with incorporation of rubber crumbles and rubber fibres up to 5% and 7.5%, respectively.

4. Gradual increment in peak axial strain at failure was noticed as the amount of rubber crumbles and rubber fibres was increased in clay. No improvement in diametral strain was observed beyond 5% inclusion of rubber crumbles and rubber fibres. Rubber

crumbles and rubber fibres have improved the post peak behaviour in compression and tension.

5. From the unconfined compressive strength and split tensile strength test on cement, stabilized clayey soil incorporated with rubber crumbles and rubber fibres, it was observed that inclusion of cement in clayey soil increased the strength of clayey soil. As the rubber content in cemented clayey soil was increased, a reduction in strength was observed. The rate of reduction in strength was found more at higher rubber content.
6. The absolute toughness of cement stabilized clayey soil in which 5% rubber crumbles and 7.5% rubber fibres were incorporated is higher than the other incorporations. The inclusion of rubber crumbles and rubber fibres up to 5% and 7.5%increased the toughness index of the composite in both compression and tension.
7. The incorporation of rubber crumbles and rubber fibres in cemented clay decreased the stiffness and loss of post peak strength of the composite. The brittle behavior of cement-stabilized clayey soil under compressive load has prosperously overcome with the inclusion of rubber fibres by lowering the rate of loss of post-peak strength. The impact of rubber crumbles in improving the post-peak reaction of cement clay soil under tensile weight was ineffective. The inclusion of rubber fibres improved the post-peak response of cemented clayey soil under tension as well.
8. The strain hardening and confinement effect induced by the 2.5% rubber crumbles/fibres content in clayey soil stabilized with 6% cement content was overshadowed by cementation effect for both compression and tension. The axial and diametral strain of clayey soil-cement-rubber crumbles/fibres specimens were found maximum at 5% and 7.5% rubber crumbles and rubber fibres content, respectively.
9. The rubberized cement stabilized clay specimens fail at relatively higher axial strain as compared to cement stabilized clay specimens. The maximum strain corresponding to peak stress is found for cemented clay specimens containing 7.5% rubber fibres.
10. The unconfined compressive strength, split tensile strength, absolute toughness, axial strain at failure and diametral strain of clayey soil-cement-rubber crumbles/fibres increased with the increase in curing period.

11. The specimens of clayey soil stabilized with 3% cement content incorporated with more than 5% rubber crumbles and rubber fibres were disintegrated, when immersed into water for curing. It shows the ineffectiveness of low cement content in the stabilization of clayey soil-rubber crumbles/fibres mixtures.
12. Due to soaking, a significant loss in unconfined compressive strength and split tensile strength was observed.
13. From the results of California Bearing Ratio test, it was noticed that the soaked California Bearing Ratio values of clayey soil incorporated with rubber crumbles and rubber fibres are lower than 10%. The soaked California Bearing Ratio values of clayey soil-cement-rubber crumbles/fibres mixtures was observed to be increased with the increase in cement content and decreased with the increase in rubber content.
14. From the one dimensional consolidation test, it was observed that with the increase in cement content, the compression index of clayey soil decreased. It increases with the increase in rubber crumbles and rubber fibres content in cemented clayey soil.
15. From the swelling pressure test of clayey soil-cement-rubber crumbles/fibres, a gradual decrease in swelling pressure was noticed, as the amount of rubber content and cement was increased.
16. From the wet/dry cycles durability test, it was noticed that the uncemented specimens of clayey soil incorporated with rubber crumbles/fibres were unable to sustain the first cycle of wet/dry test. An increase in weight loss was observed for the clayey soil stabilised with 6% cement content, with the increase in rubber crumbles/fibres content.
17. Cavities and micro cracks were observed in the rubber fibres, which reduced the strength of composite. Micro structural analysis shows the weak interface between rubber crumbles/fibres and cemented clayey soil.
18. It was noted from the study that rubber fibres have relatively better performance than rubber crumbles when cement is incorporated in clayey soil.

8.2 CONCLUDING REMARKS

Overall, the thesis has attempted to provide an insight into the various aspects of investigation of uncemented/cemented clayey soil incorporated with rubber crumbles/fibres through laboratory study and brought out their application in a typical field situation as mentioned below:

- The cemented clayey soil mixed with 2.5% to 10% rubber crumbles and rubber fibres have satisfied the required criteria of density for embankment construction of height 3 m (max.) for rural roads, which is not subjected to extensive flooding. The uncemented clayey soil mixed with rubber crumbles and rubber fibres up to 5% have satisfied the density requirement for embankment (for rural roads) of height more than 3 meters. The clayey soil stabilized with 3% cement incorporated with 2.5% to 5% rubber crumbles and 2.5% to 5% rubber fibres have satisfied this criterion. Similarly, the clayey soil stabilized with 6% cement incorporated with 2.5% rubber crumbles and 2.5% to 5% rubber fibres have satisfied this criterion.
- The soaked California Bearing Ratio values of clayey soil incorporated with rubber crumbles and fibres is less than 10%. Therefore, the pre-requisite treatment of clayey soil incorporated with rubber crumbles and fibres is needed for its application in sub grade and sub base. The soaked California Bearing Ratio values of clayey soil stabilized with 3% cement containing 2.5% to 7.5% rubber crumbles and rubber fibres have satisfied all the criteria of various codal provisions for its application in sub grade and sub base course. Whereas, the soaked California Bearing Ratio values of 6% cement stabilized clayey soil incorporated with rubber crumbles and rubber fibres have been found more than the requirements of Indian standards for all percentage of rubber content.
- The clayey soil-cement-rubber crumbles and clayey soil-cement-rubber fibres mixtures containing 3% cement do not satisfy the codal provisions for its application in slide slope of canal. The clayey soil mixed with 6% cement and 5% to 10% rubber crumbles have swelling pressure less than 20%. Similarly, the swelling pressure of clayey soil stabilized with 6% cement containing 2.5% to 10% rubber fibres have satisfied the criteria of maximum swelling pressure.
- The durability of clayey soil mixed with rubber crumbles and rubber fibres is questionable. The clayey soil treated with 3% cement, 2.5% to 10% rubber crumbles, and rubber fibres do not satisfy the criteria of weight loss for its application in base courses and sub base courses of pavements. The optimum dose of rubber fibres in the clayey soil stabilized with 6% cement is 2.5% for its application in base course of road pavement. Similarly, the rubber crumbles and rubber fibres up to 5% and 7.5%

respectively could be incorporated successfully in clayey soils stabilized with 6% cement for its application in sub base course of road pavements.

However, the postulated behaviour needs to be supplemented subsequently with field trials.

To sum up, the maximum percentage of rubber crumbles and rubber fibres content that can be incorporated in cement stabilized clayey soil should not be more than 5% and 7.5%, respectively. The proposed perspective for disposal/utilization of waste tire would not only effectively mitigate the detrimental effects on health, environment, and ecological systems, but also efficient to enhance the engineering properties of cemented clay in totality. The incorporation of rubber crumbles/fibres in uncemented/cemented clay can be one of the congenial methods of the disposal of this inexpedient waste because an enormous quantity of rubber waste can be consumed in construction of voluminous structures such as backfill behind the retaining walls, embankments of rural roads, subgrade, sub base of rural roads, side slope of canal etc.

8.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The present studies may be extended in future for the following:

1. Studies are required to be conducted to analyze the triaxial, flexural, leachate and drainage behaviour of the clayey soil, cement mix mixed with rubber crumbles/fibres.
2. Behaviour of uncemented/cemented clayey soil incorporated with rubber crumbles/fibres against tube suction and freeze/thaw are needed to be studied.
3. In our study, weak interface between rubber crumbles/fibres and cemented clayey soil was observed. The impact of rubber crumbles/fibres treated with NaOH or $CaCO_3$ on geotechnical properties of clayey soil stabilized with lime/cement is needed to be studied.
4. Studies focus on the use of other industrial wastes with clayey soil-rubber crumbles/fibres mixture can be one of the topics for further investigation.
5. The utilization of waste rubber tubes in the cement or lime stabilized clayey soil can be one of the topics for further investigation.
6. Experimental model embankment and roads pavement studies on cement stabilized clayey soil incorporated with rubber crumbles/fibres can be carried out in laboratory or in the field.

7. Evaluation of dynamics properties such as damping ratio, shear modulus of clayey soil-cement-rubber crumbles/fibres mixture is still needed to be studied.
8. Studies are required to perform numerical modelling of the material.

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APPENDIX

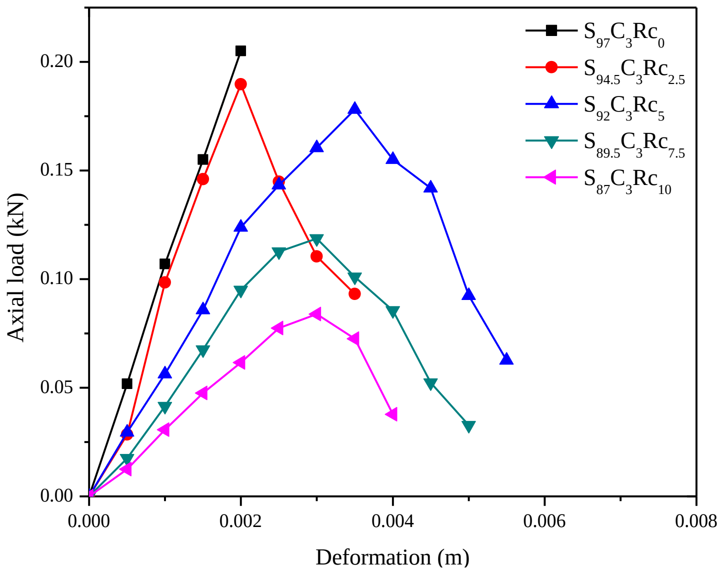

Fig. A1 Axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 7 days (Unsoaked condition)

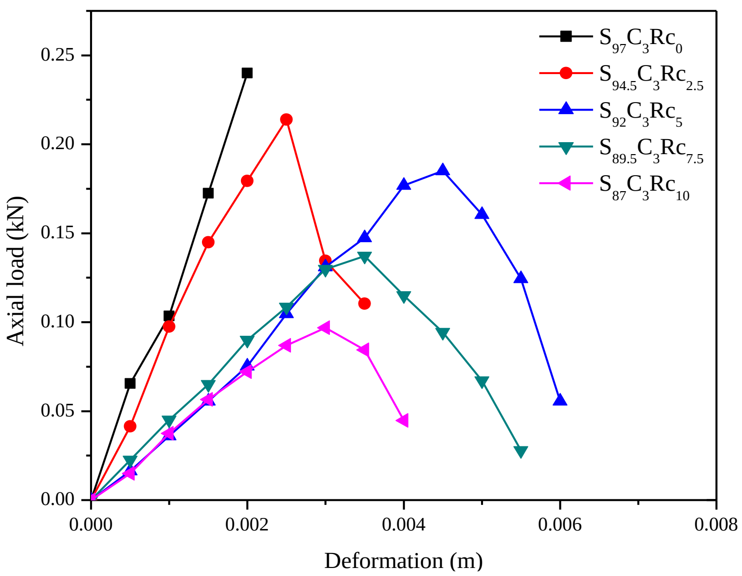

Fig. A2 Axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 14 days (Unsoaked condition)

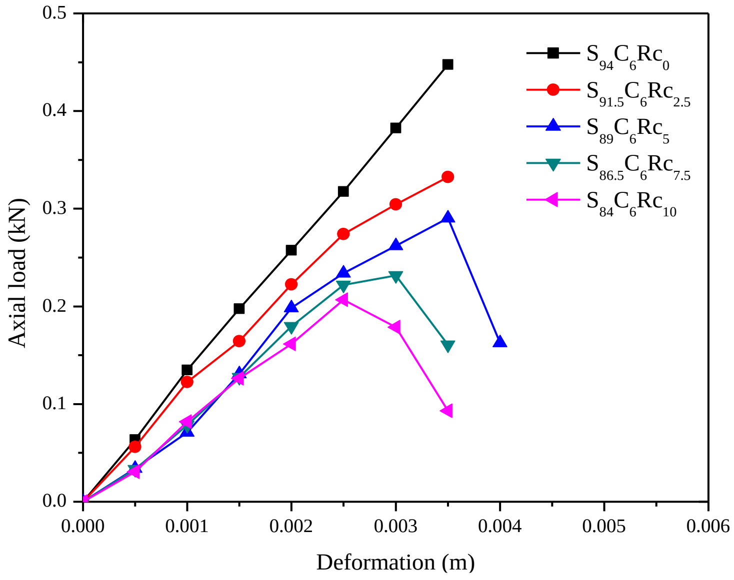

Fig. A3 Axial load- deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 7 days (Unsoaked condition)

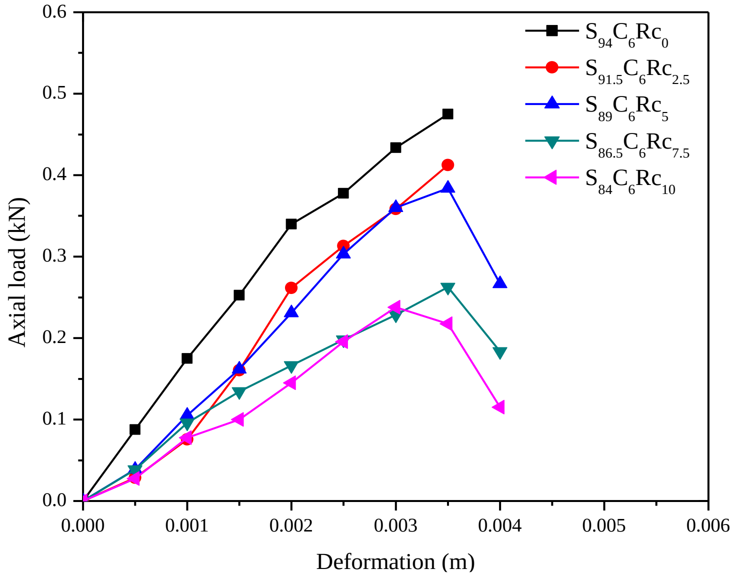

Fig. A4 Axial load- deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 14 days (Unsoaked condition)

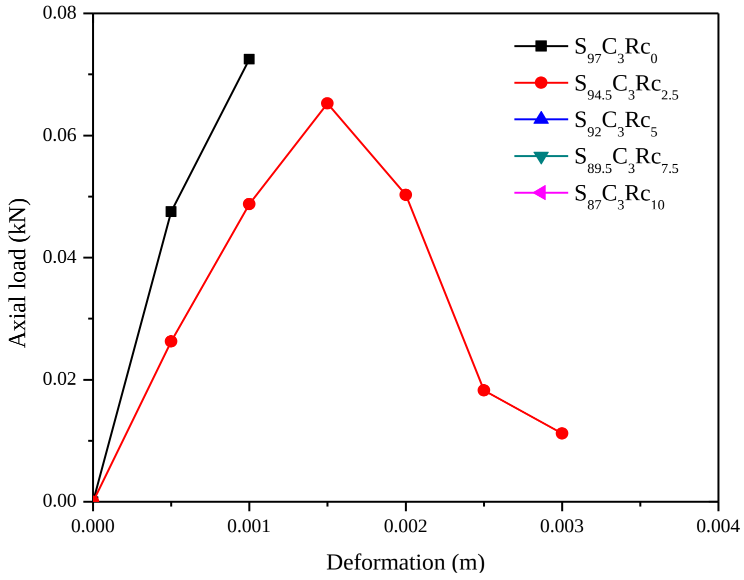

Fig. A5 Axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 7 days (Soaked condition)

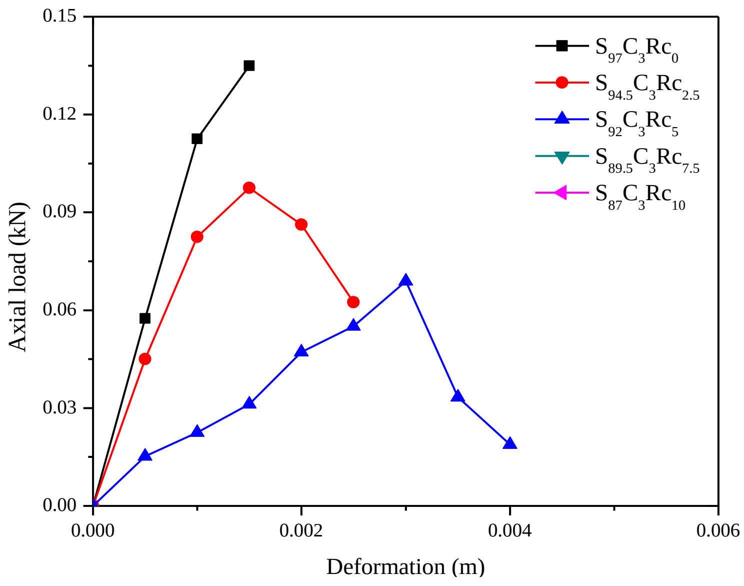

Fig. A6 Axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 14 days (Soaked condition)

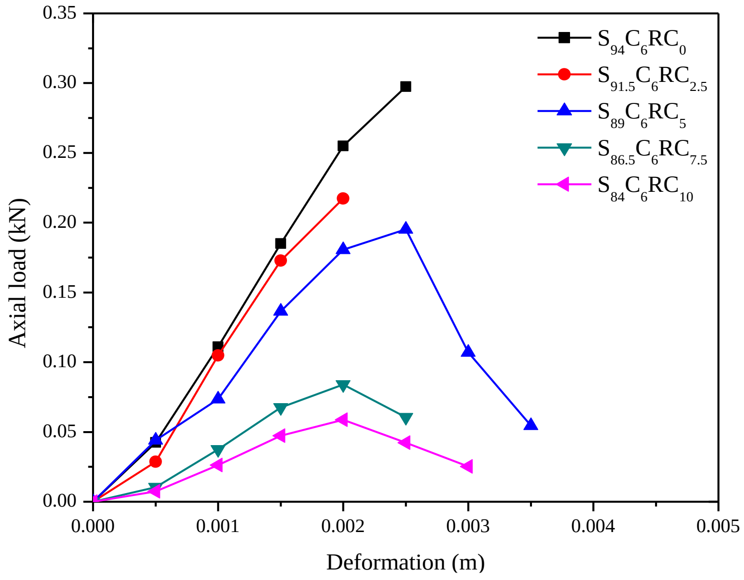

Fig. A7 Axial load- deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 7 days (Soaked condition)

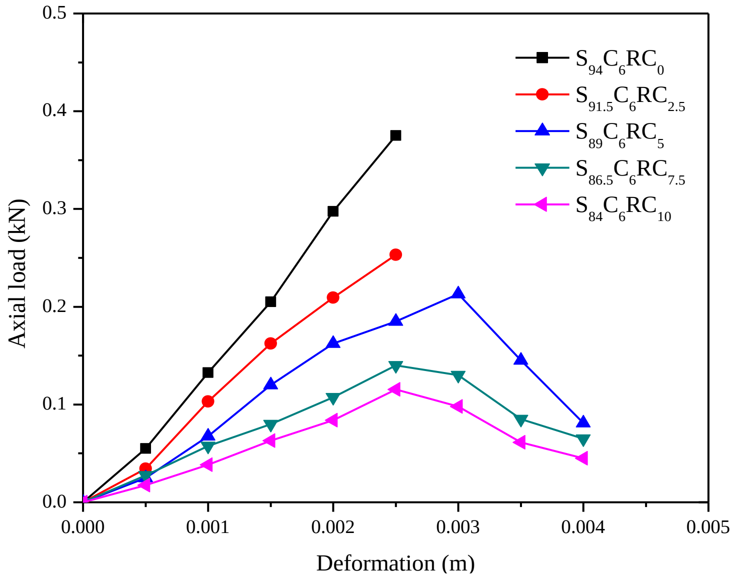

Fig. A8 Axial load- deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 14 days (Soaked condition)

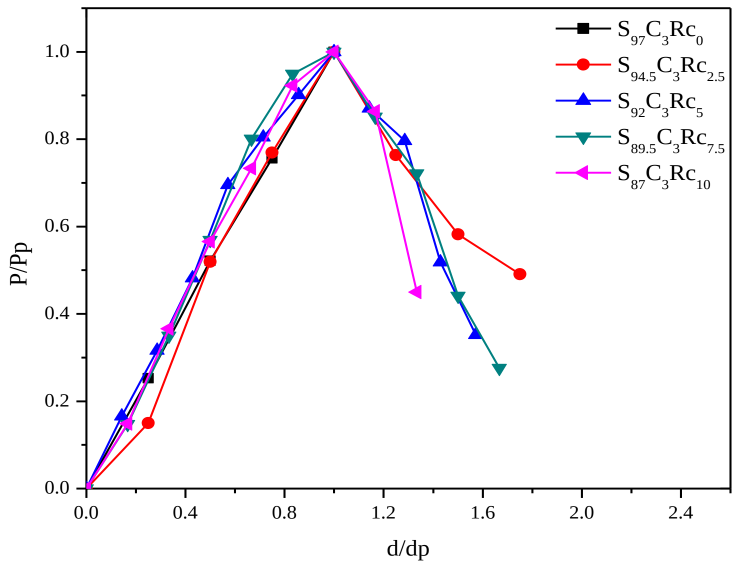

Fig. A9 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 7 days (Unsoaked condition)

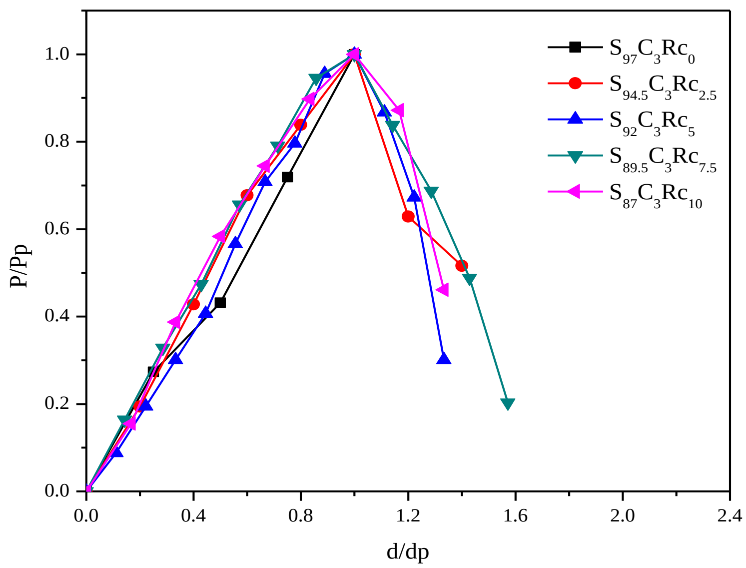

Fig. A10 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 14 days (Unsoaked condition)

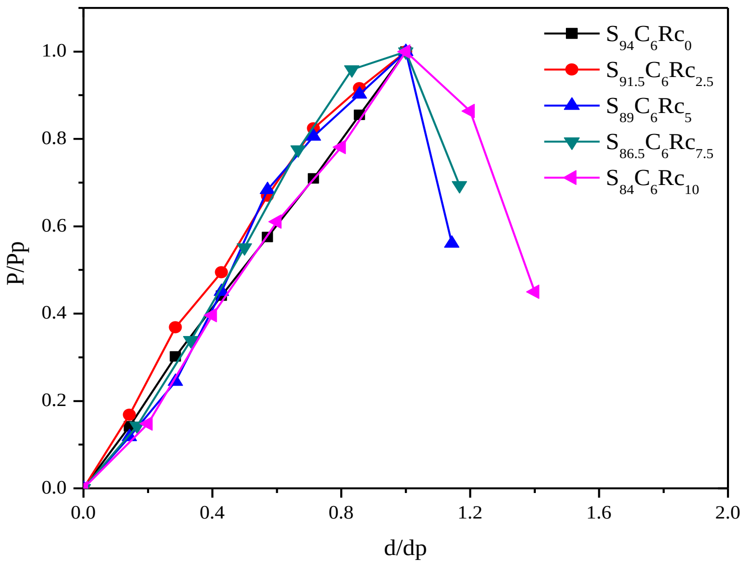

Fig. A11 Normalized axial load- deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 7 days (Unsoaked condition)

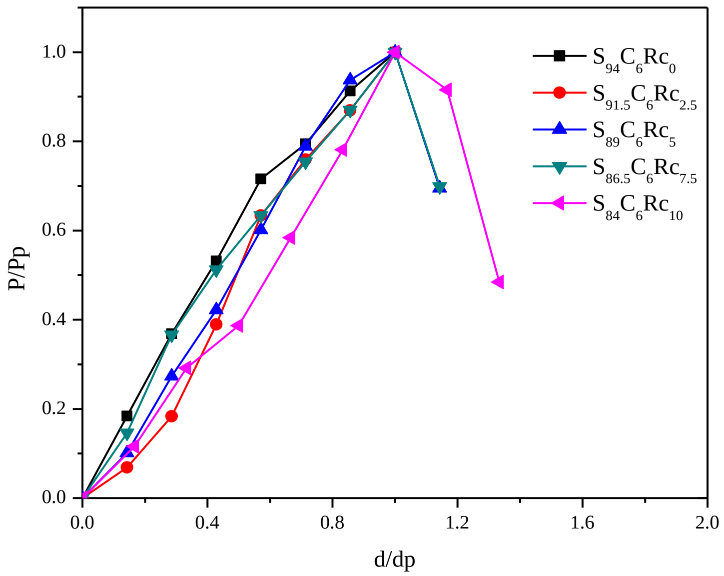

Fig. A12 Normalized axial load- deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 14 days (Unsoaked condition)

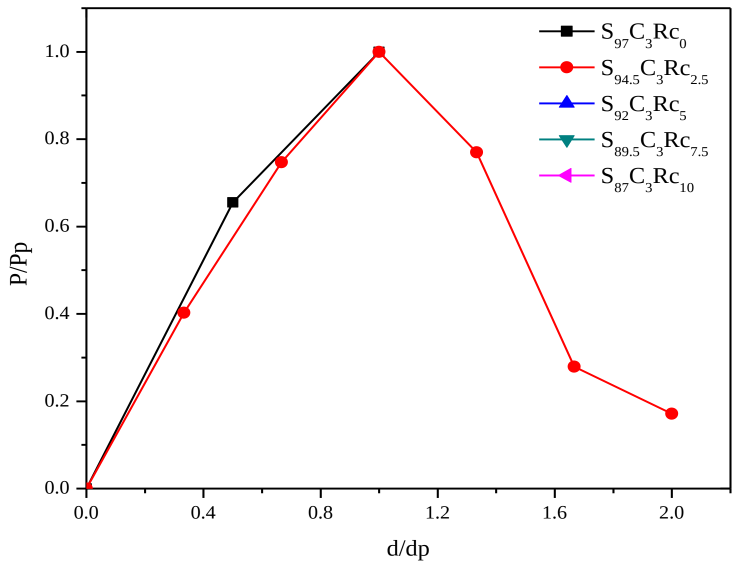

Fig. A13 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 7 days (Soaked condition)

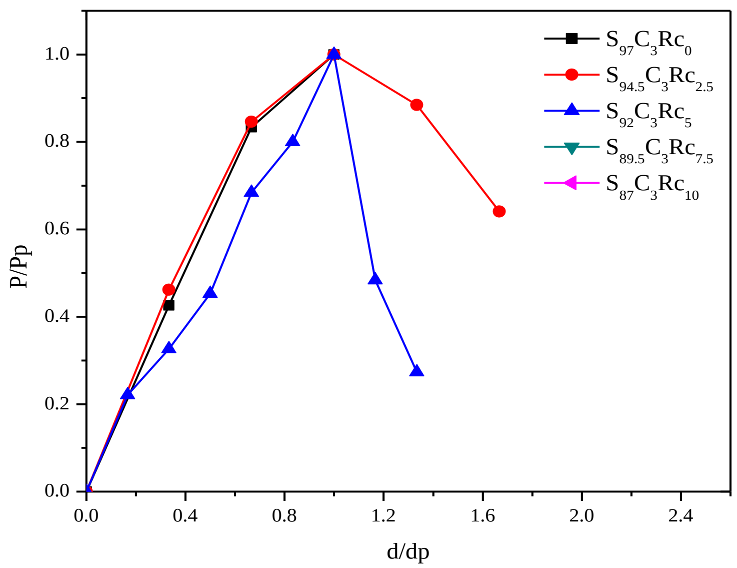

Fig. A14 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 14 days (Soaked condition)

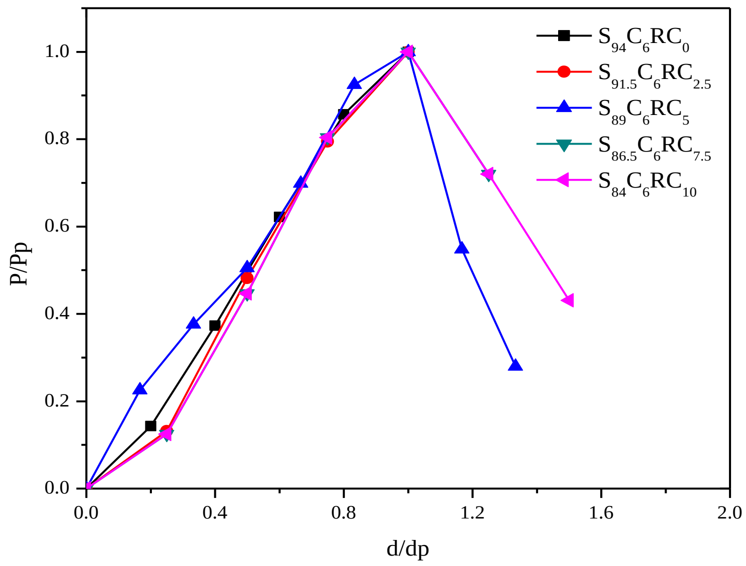

Fig. A15 Normalized axial load- deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 7 days (Soaked condition)

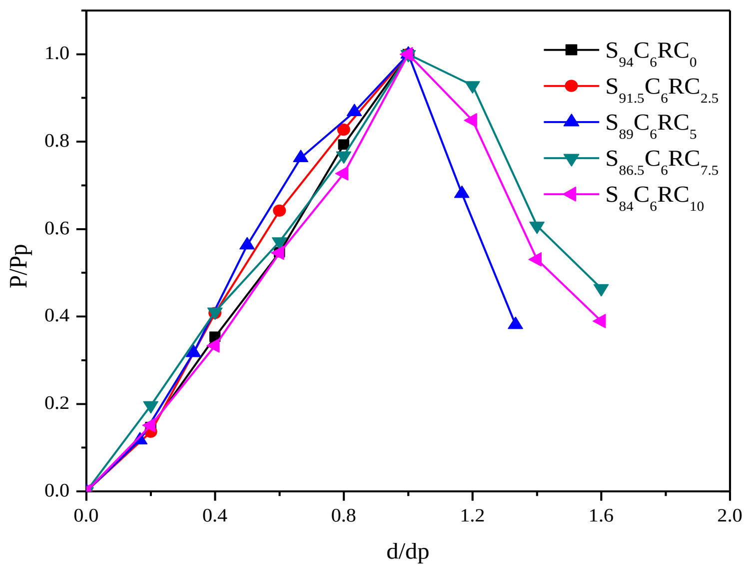

Fig. A16 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 14 days (Soaked condition)

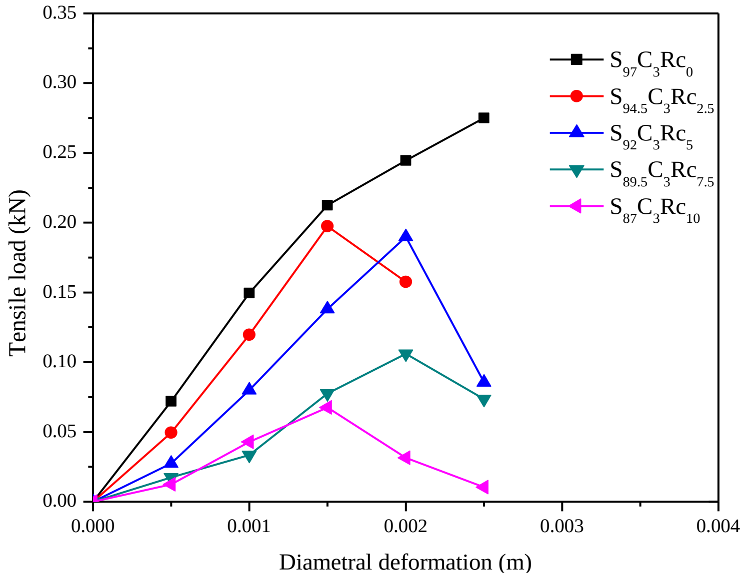

Fig. A17 Tensile load-diametral deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 7 days (Unsoaked condition)

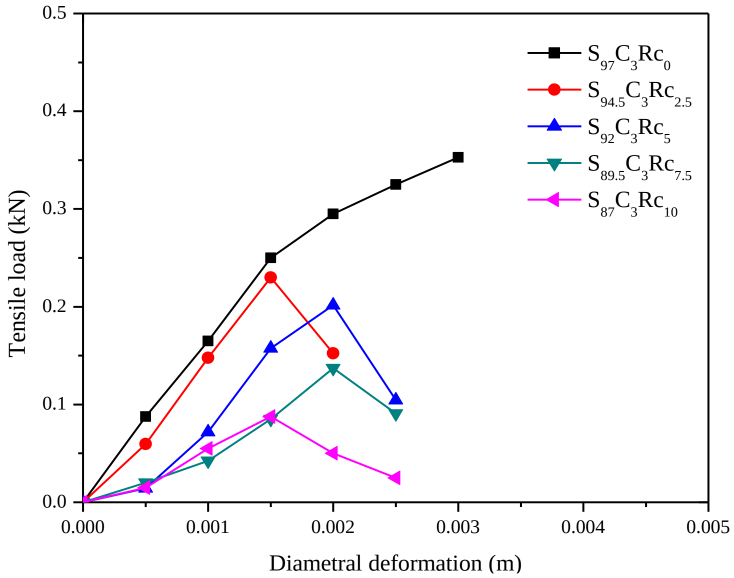

Fig. A18 Tensile load-diametral deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 14 days (Unsoaked condition)

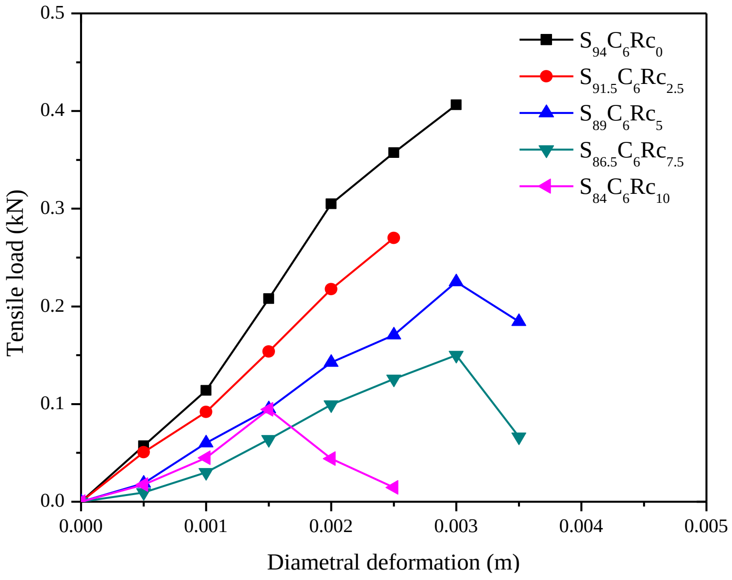

Fig. A19 Tensile load-diametral deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 7 days (Unsoaked condition)

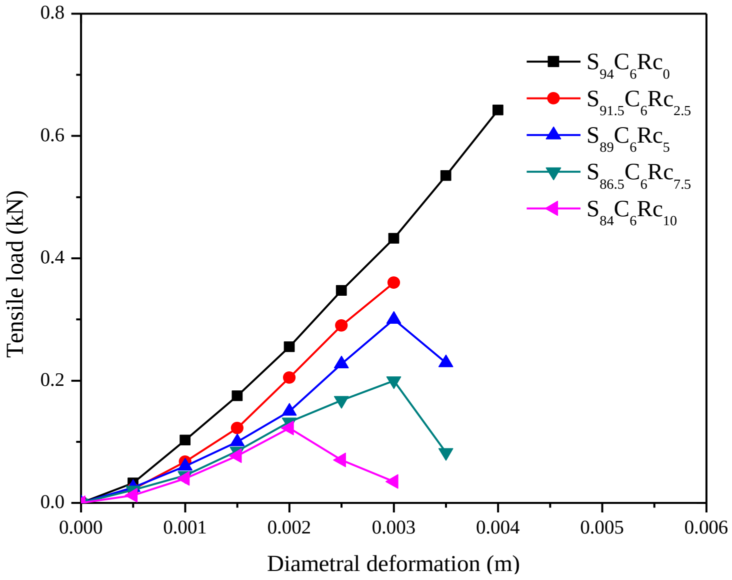

Fig. A20 Tensile load-diametral deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 14 days (Unsoaked condition)

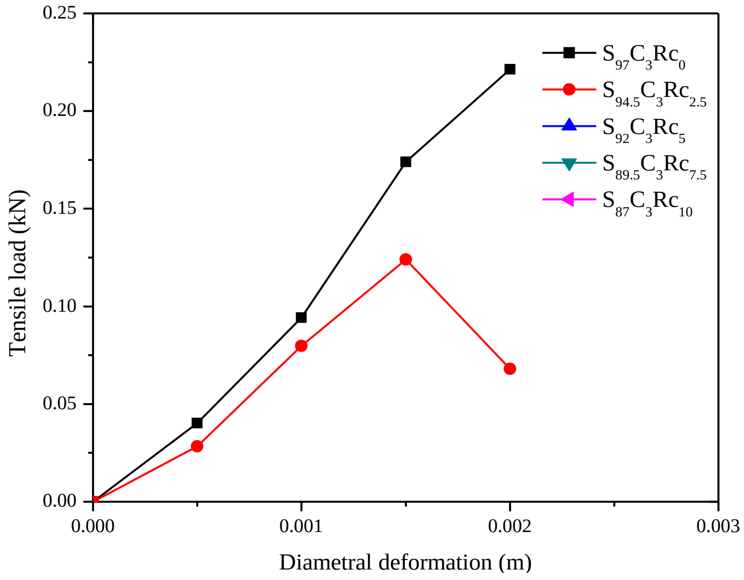

Fig. A21 Tensile load-diametral deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 7 days (Soaked condition)

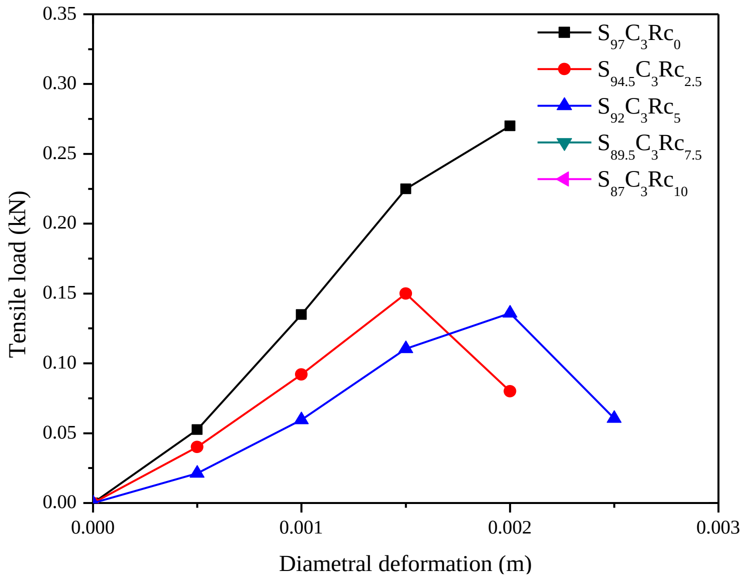

Fig. A22 Tensile load-diametral deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 14 days (Soaked condition)

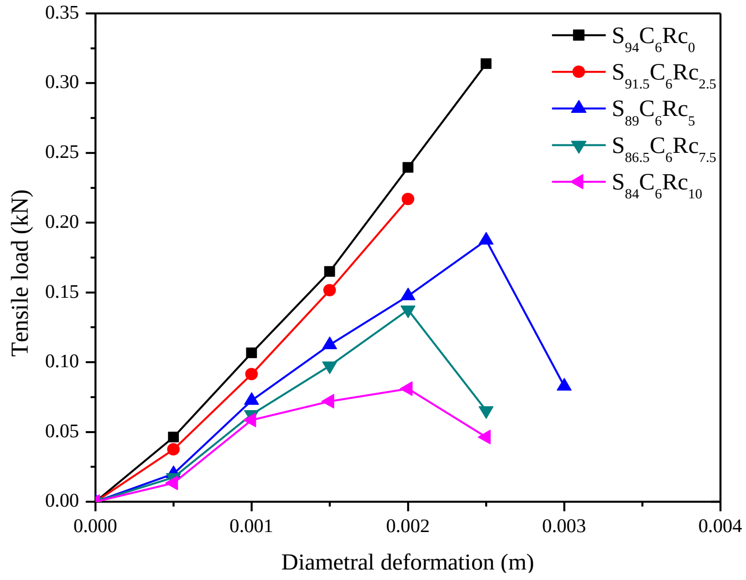

Fig. A23 Tensile load-diametral deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 7 days (Soaked condition)

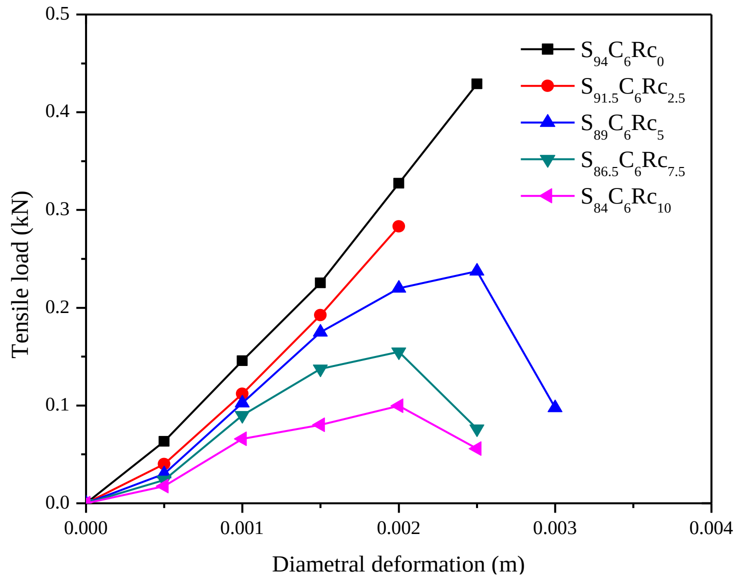

Fig. A24 Tensile load-diametral deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 14 days (Soaked condition)

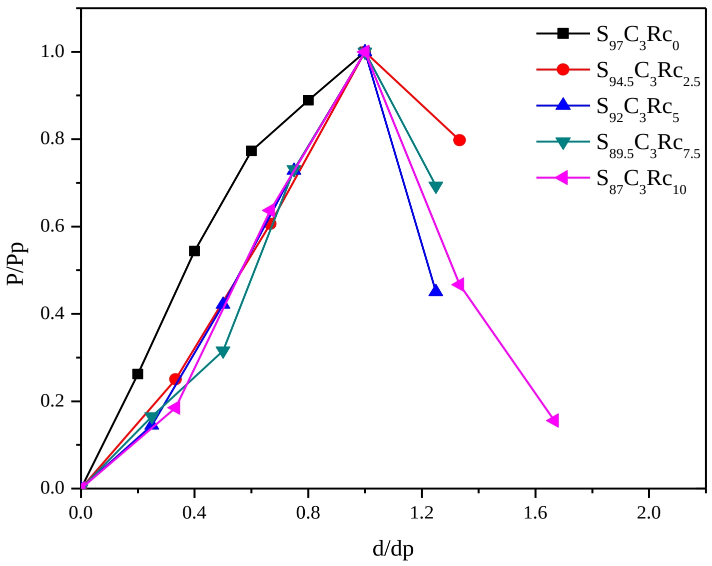

Fig. A25 Normalized tensile load-deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 7days (Unsoaked condition)

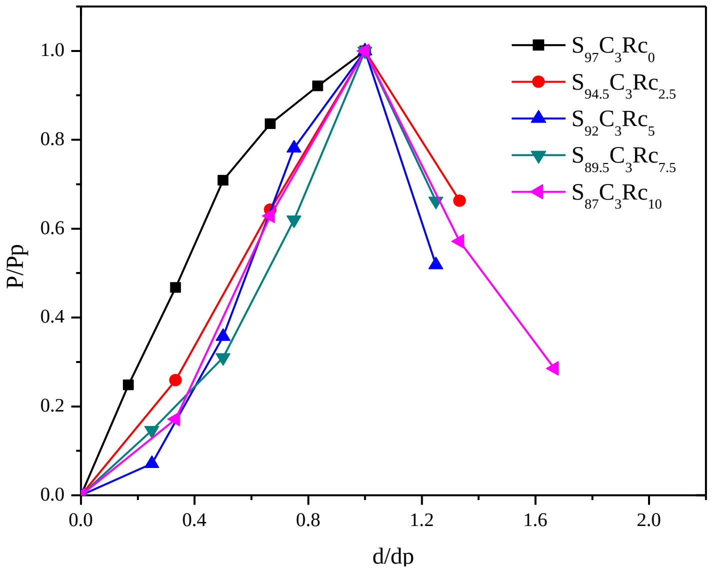

Fig. A26 Normalized tensile load-deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 14 days (Unsoaked condition)

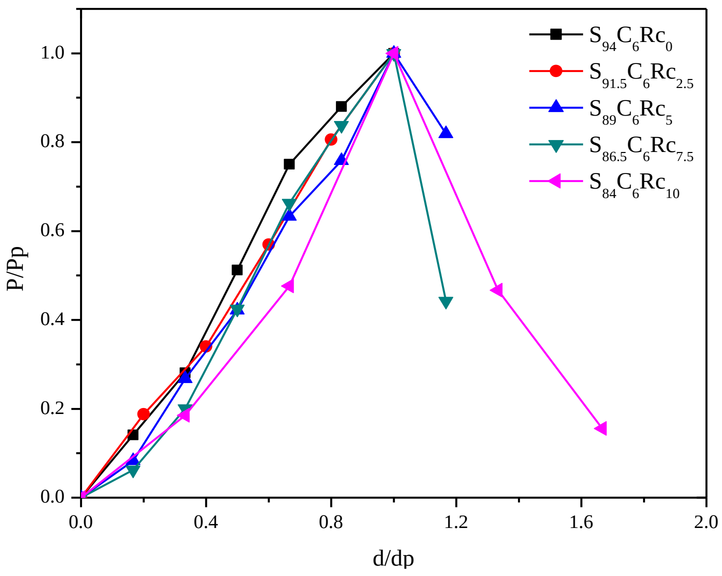

Fig. A27 Normalized tensile load-deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 7 days (Unsoaked condition)

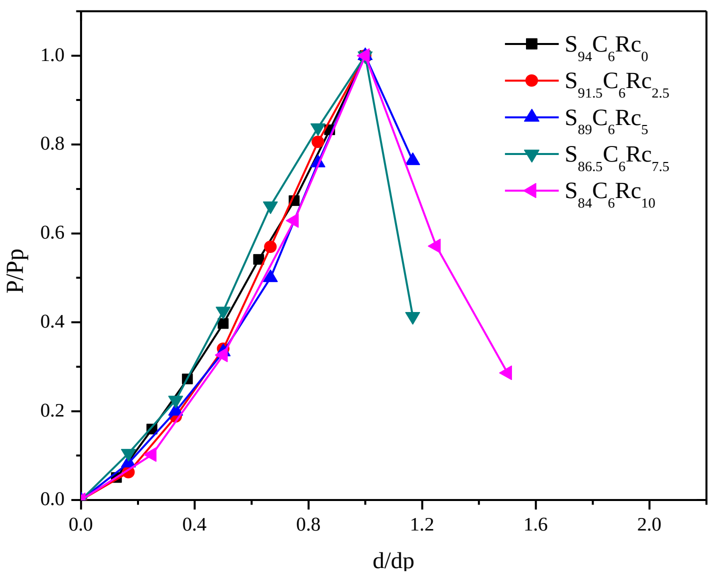

Fig. A28 Normalized tensile load-deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 14 days (Unsoaked condition)

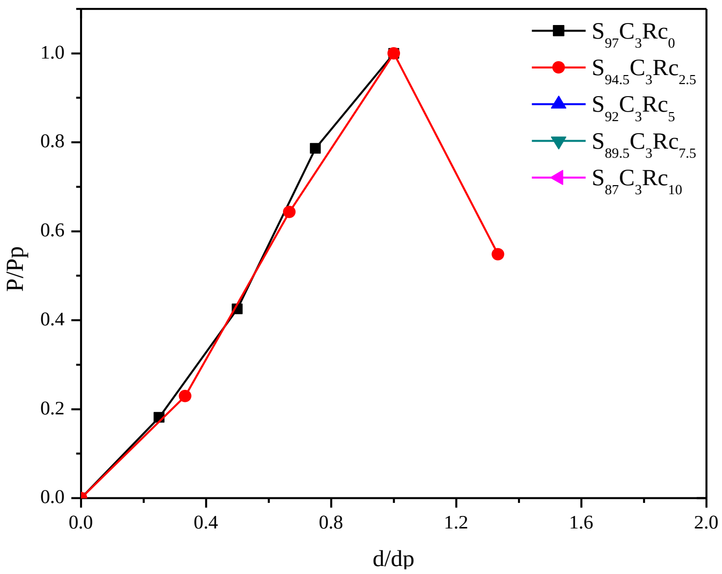

Fig. A29 Normalized tensile load-deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 7 days (Soaked condition)

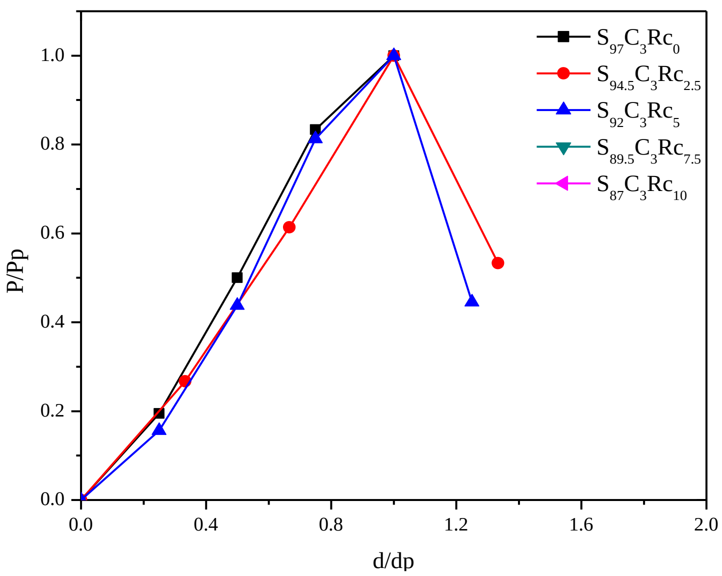

Fig. A30 Normalized tensile load-deformation curves of clayey soil mixed with 3% cement and rubber crumbles and cured for 14 days (Soaked condition)

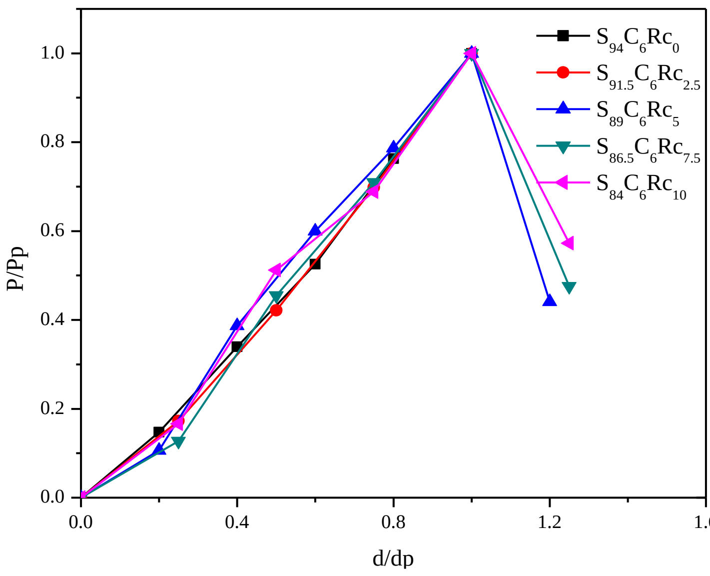

Fig. A31 Normalized tensile load-deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 7 days (Soaked condition)

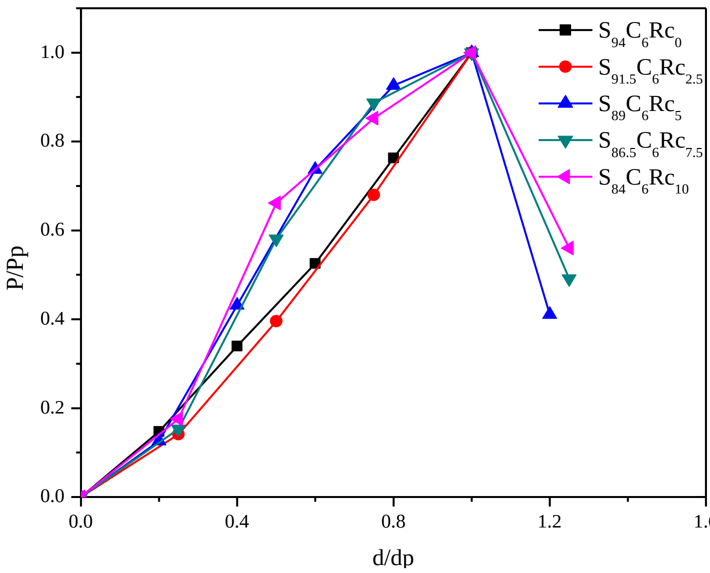

Fig. A32 Normalized tensile load-deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 14 days (Soaked condition)

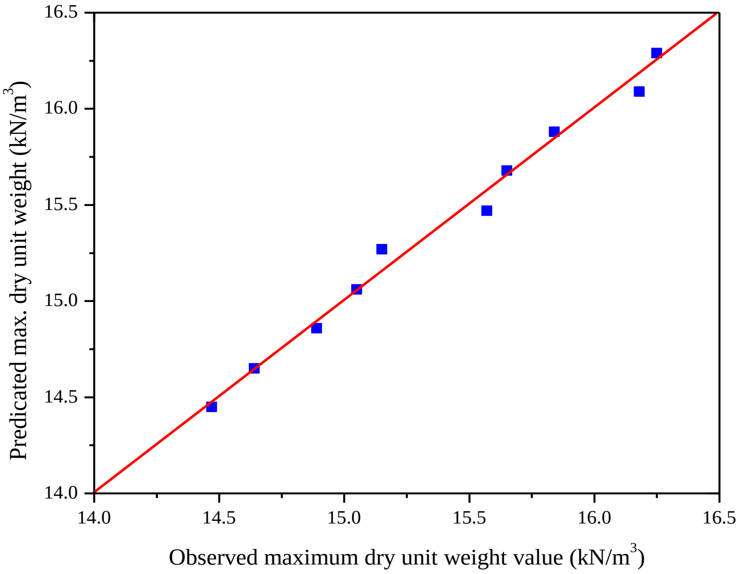

Fig. A33 Scatter plot of predicated and observed maximum dry unit weight values of clayey soil mixed with cement and rubber crumbles

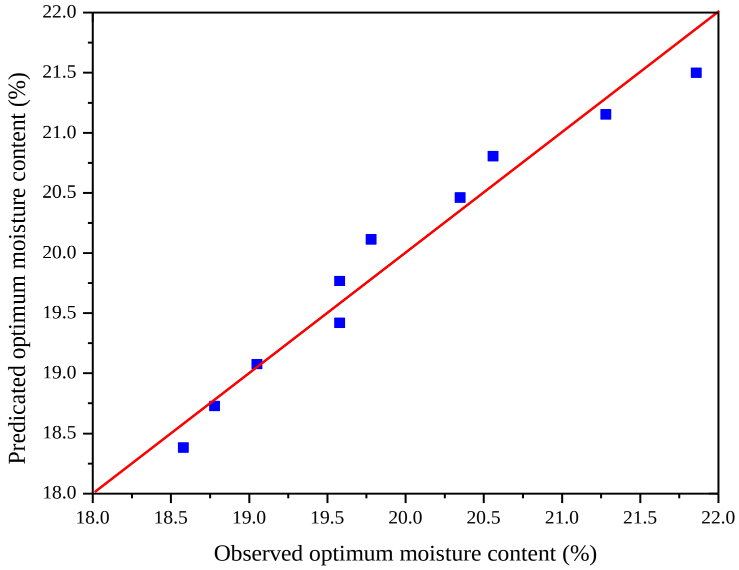

Fig. A34 Scatter plot of predicated and observed optimum moisture content values of clayey soil mixed with cement and rubber crumbles

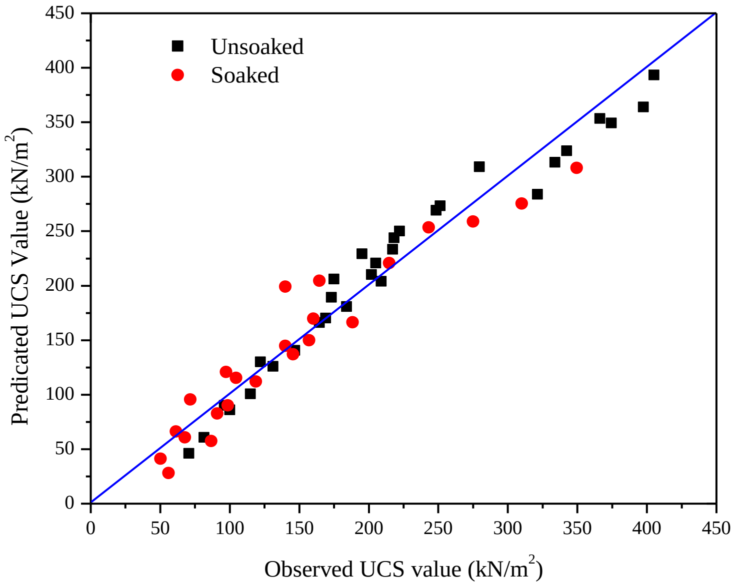

Fig. A35 Scatter plot of predicated and observed unconfined compressive strength values of clayey soil mixed with cement and rubber crumbles

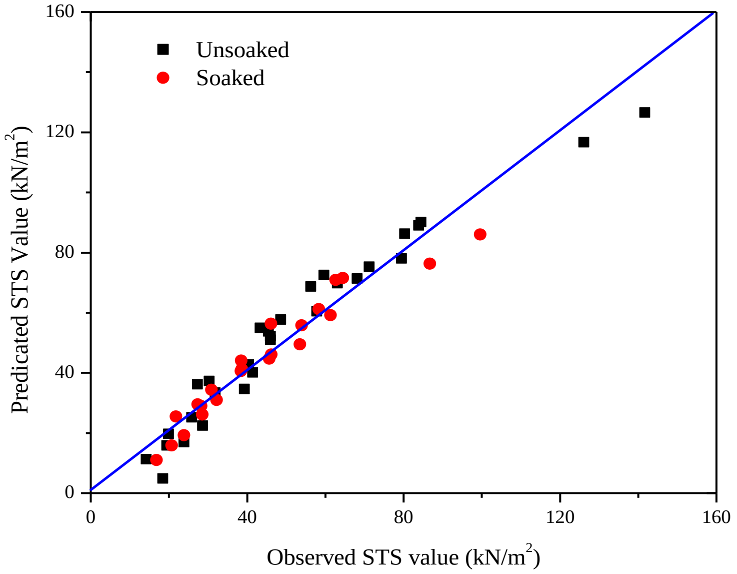

Fig. A36 Scatter plot of predicated and observed split tensile strength values of clayey soil mixed with cement and rubber crumbles

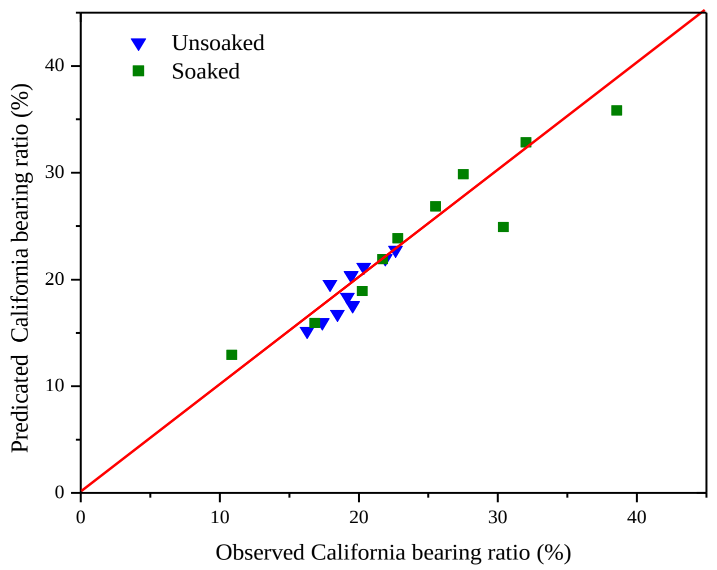

Fig. A37 Scatter plot of predicated and observed California bearing ratio (%) of clayey soil mixed with cement and rubber crumbles

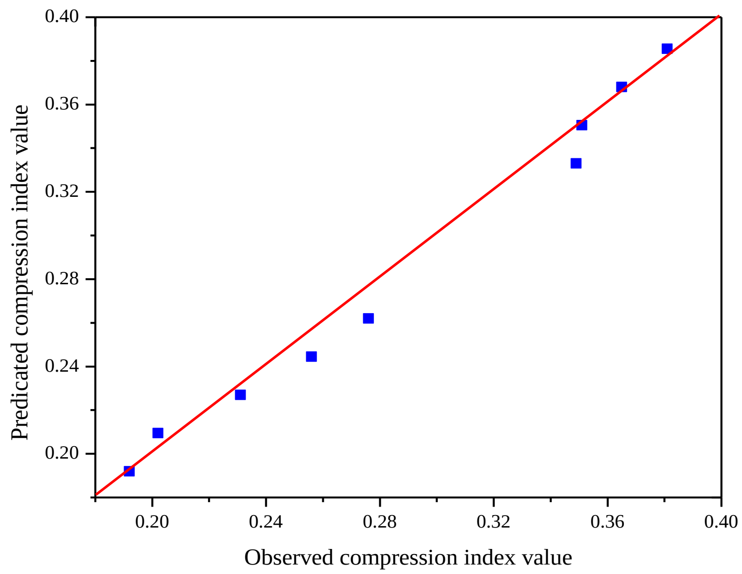

Fig. A38 Scatter plot of predicated and observed compression index values of clayey soil mixed with cement and rubber crumbles

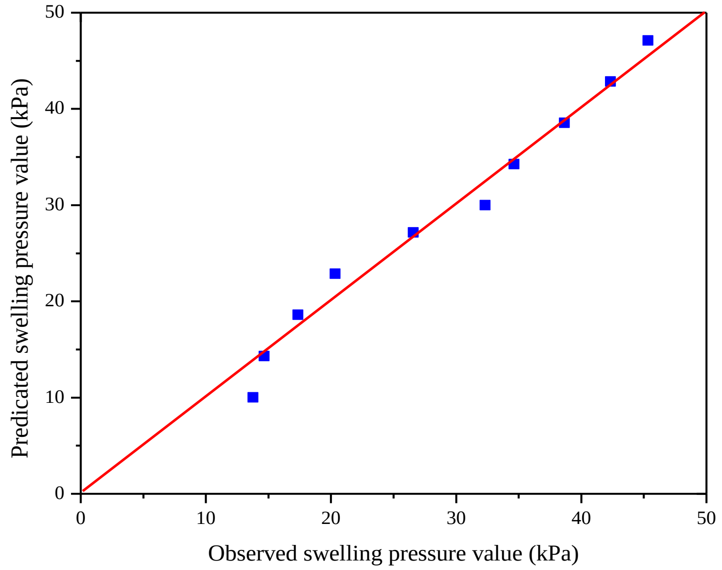

Fig. A39 Scatter plot of predicated and observed swelling pressure values of clayey soil mixed with cement and rubber crumbles

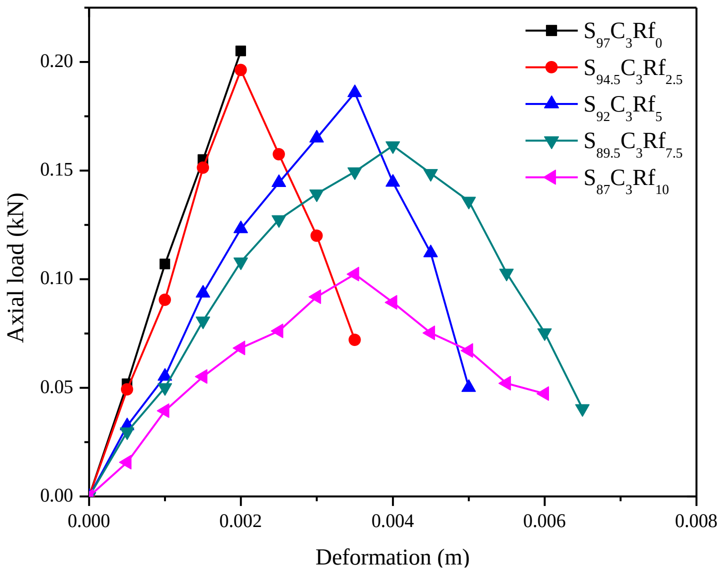

Fig. A40 Axial load- deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 7 days (Unsoaked condition)

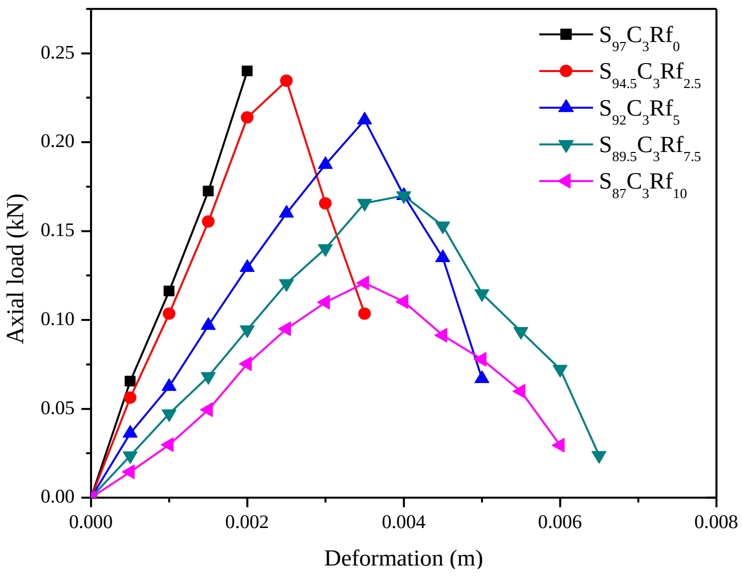

Fig. A41 Axial load- deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 14 days (Unsoaked condition)

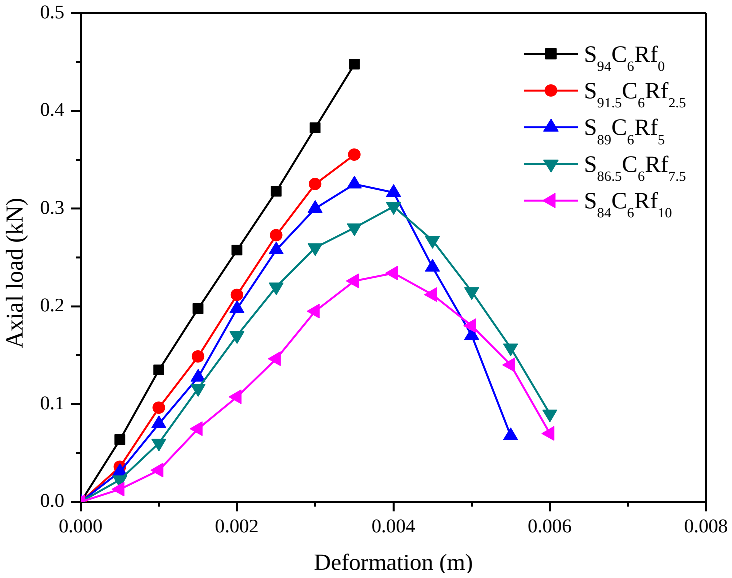

Fig. A42 Axial load- deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 7 days (Unsoaked condition)

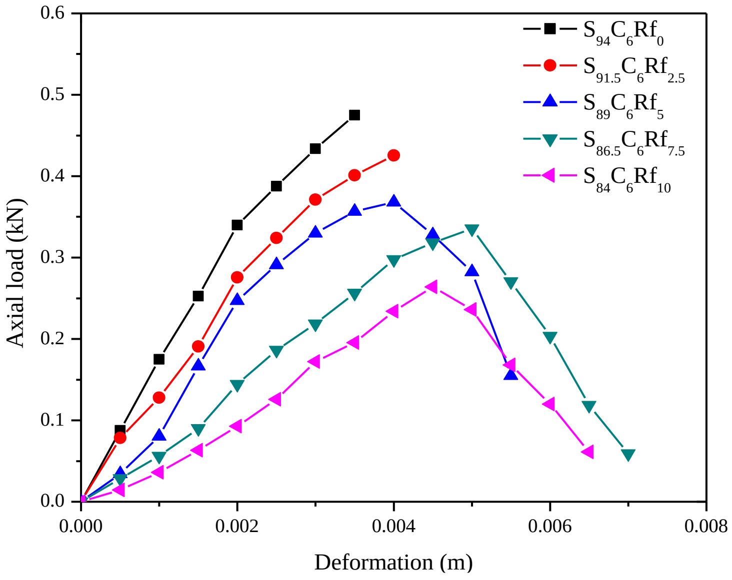

Fig. A43 Axial load- deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 14 days (Unsoaked condition)

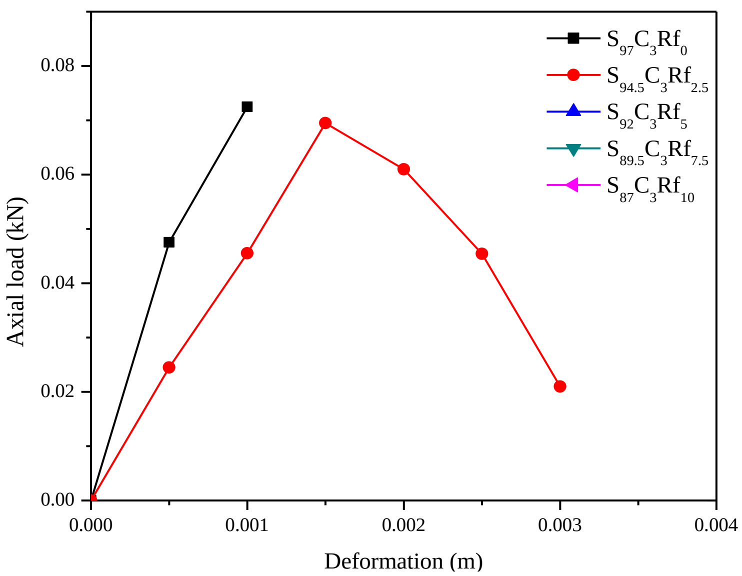

Fig. A44 Axial load- deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 7 days (Soaked condition)

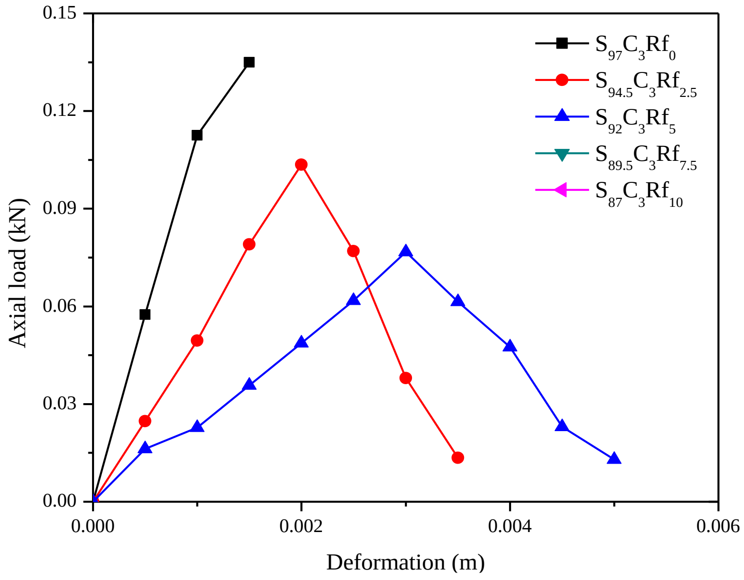

Fig. A45 Axial load- deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 14 days (Soaked condition)

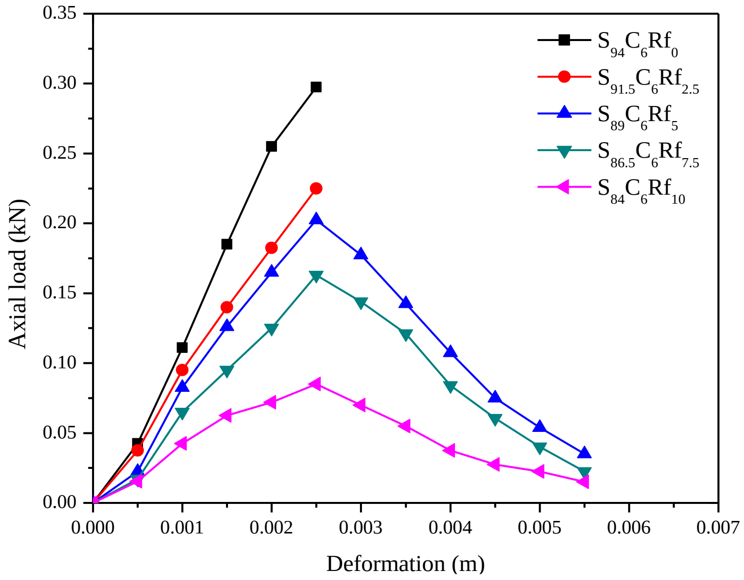

Fig. A46 Axial load- deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 7 days (Soaked condition)

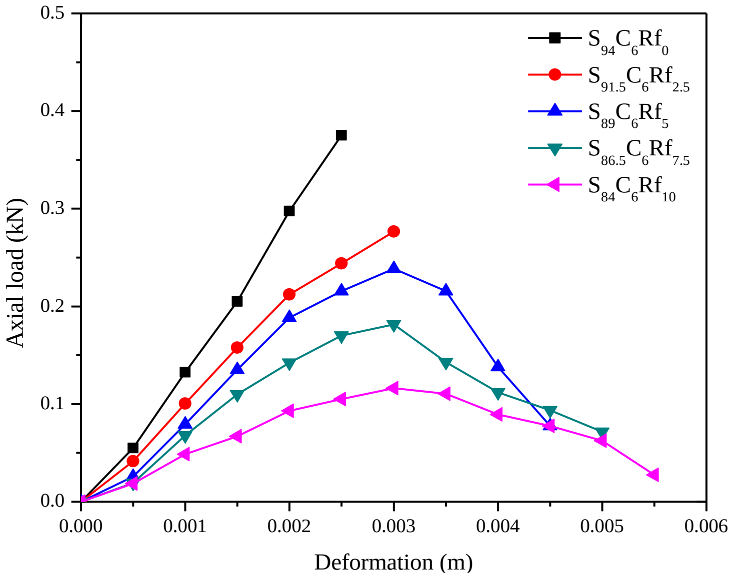

Fig. A47 Axial load- deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 14 days (Soaked condition)

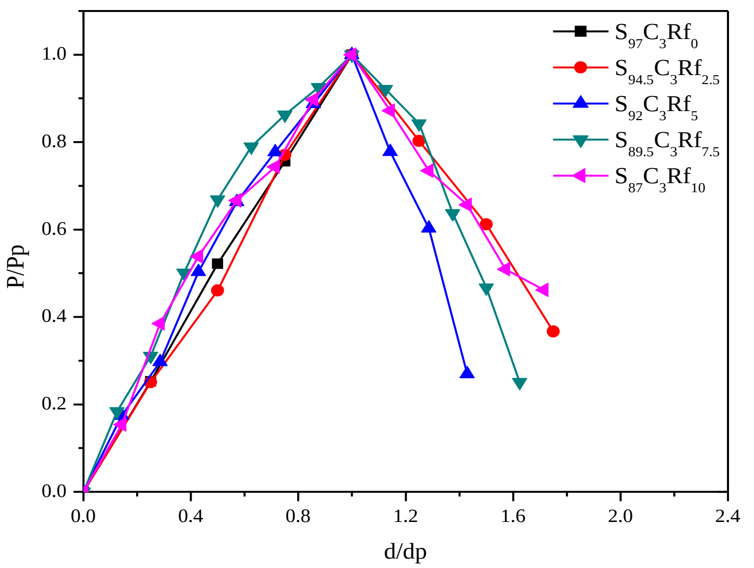

Fig. A48 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 7 days (Unsoaked condition)

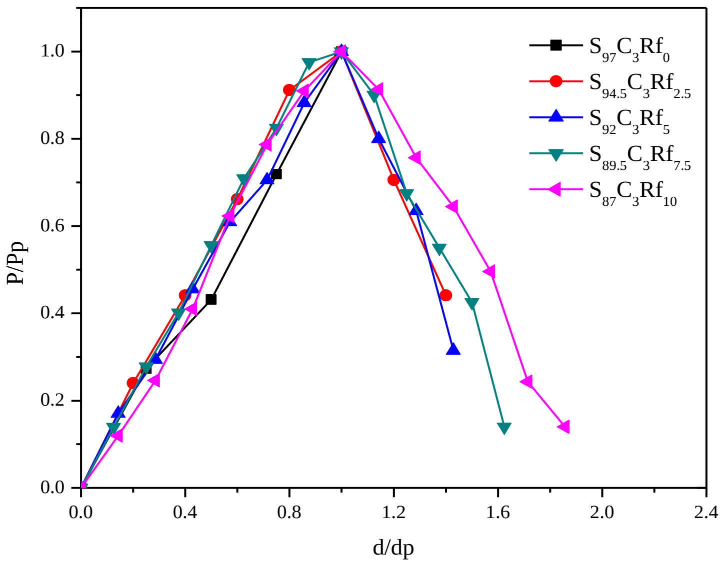

Fig. A49 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 14 days (Unsoaked condition)

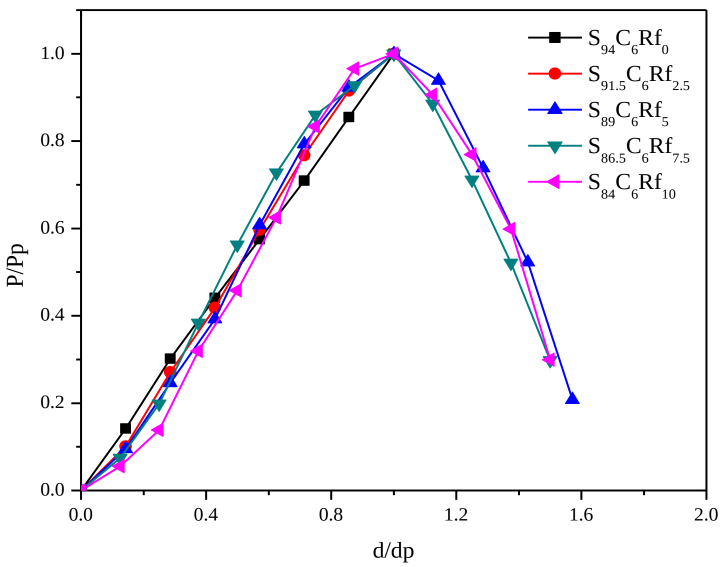

Fig. A50 Normalized axial load- deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 7 days (Unsoaked condition)

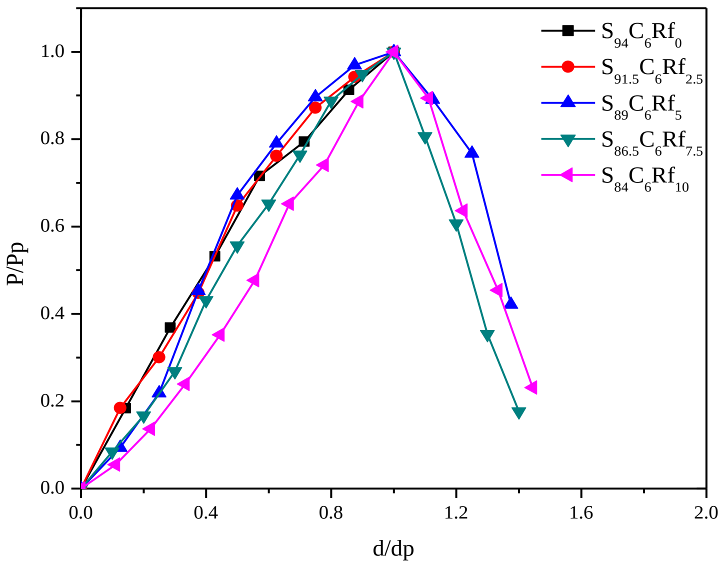

Fig. A51 Normalized axial load- deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 14 days (Unsoaked condition)

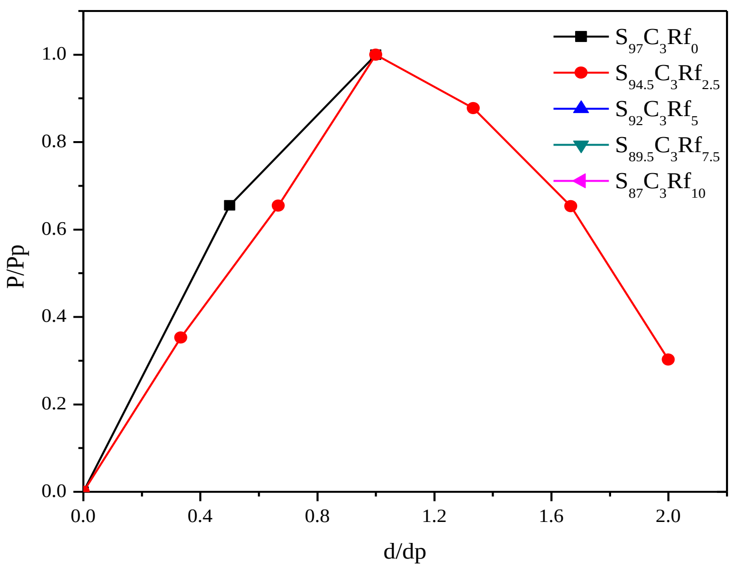

Fig. A52 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 7 days (Soaked condition)

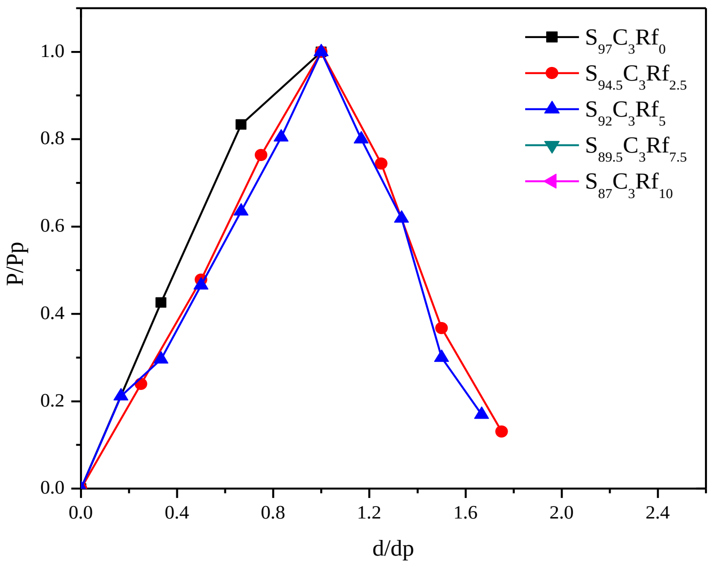

Fig. A53 Normalized axial load- deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 14 days (Soaked condition)

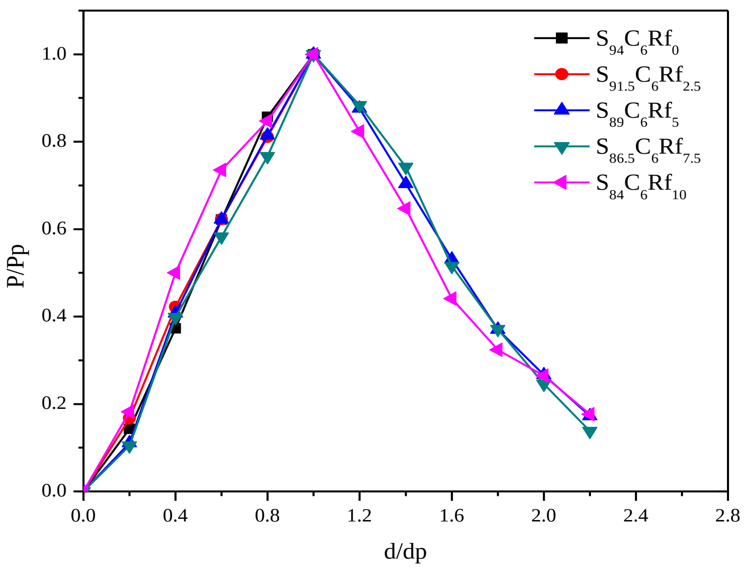

Fig. A54 Normalized axial load- deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 7 days (Soaked condition)

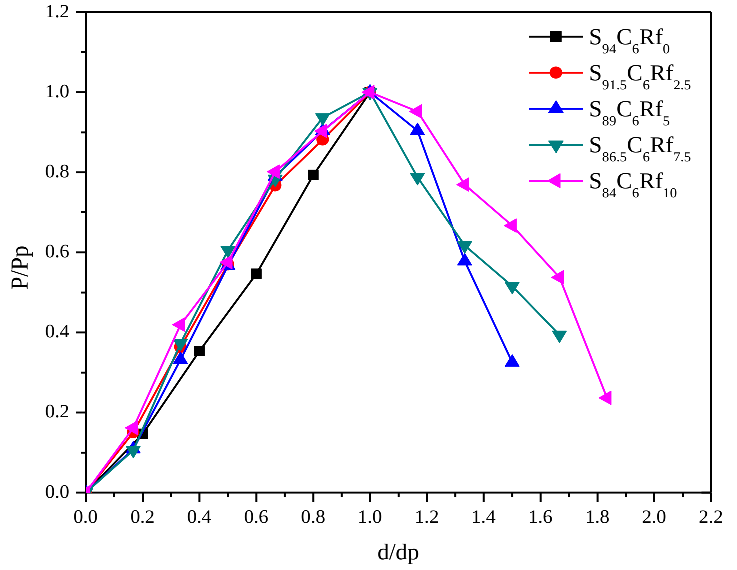

Fig. A55 Normalized axial load- deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 14 days (Soaked condition)

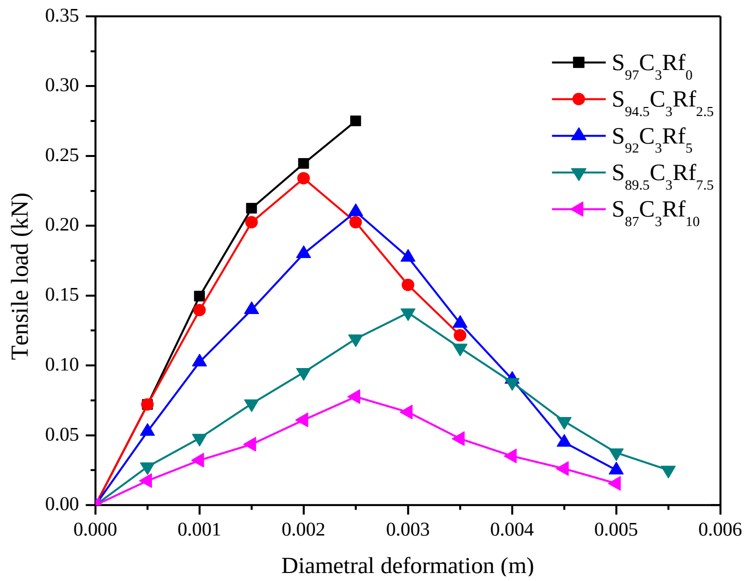

Fig. A56 Tensile load-diametral deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 7 days (Unsoaked condition)

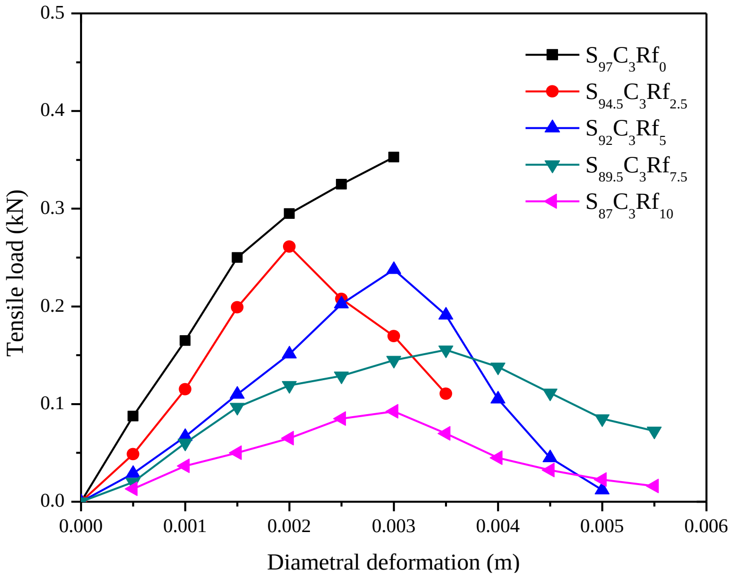

Fig. A57 Tensile load-diametral deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 14 days (Unsoaked condition)

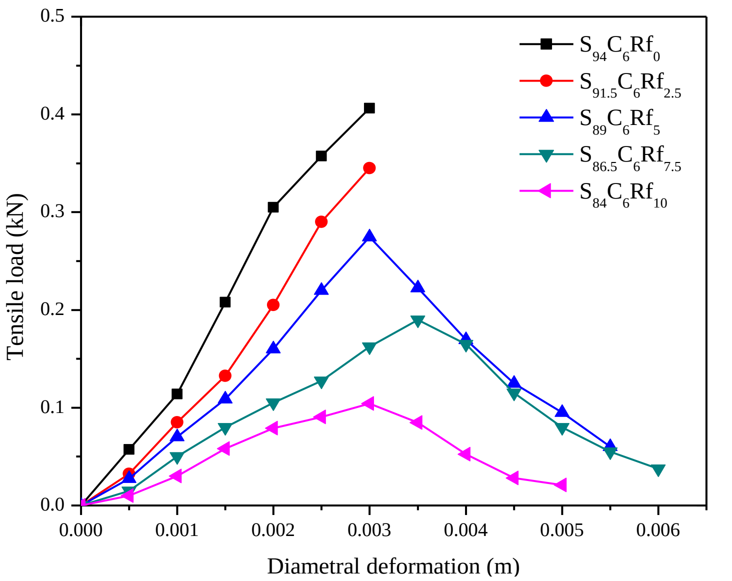

Fig. A58 Tensile load-diametral deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 7 days (Unsoaked condition)

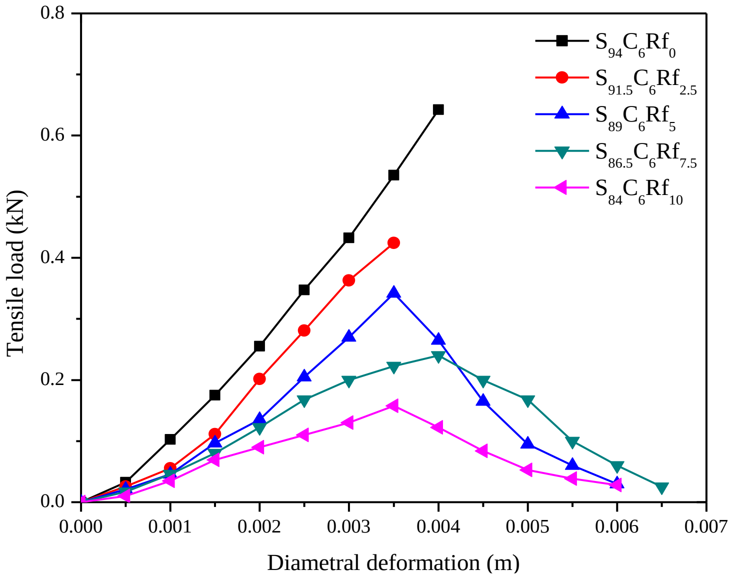

Fig. A59 Tensile load-diametral deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 14 days (Unsoaked condition)

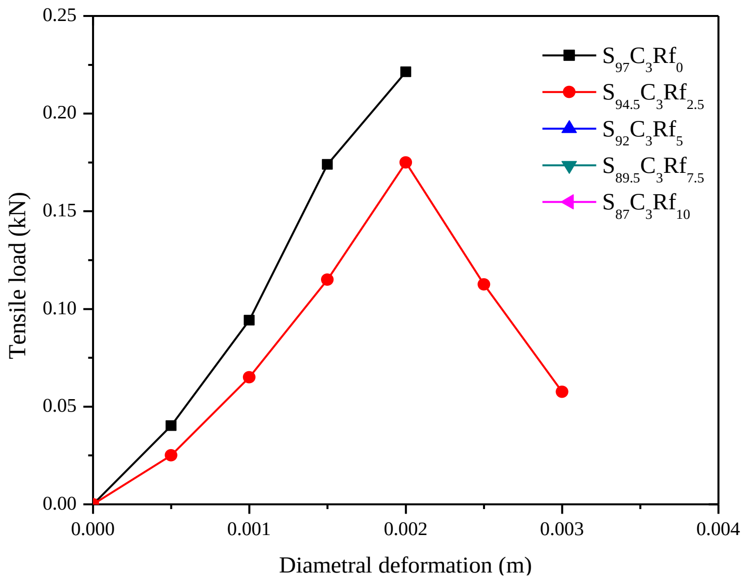

Fig. A60 Tensile load-diametral deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 7 days (Soaked condition)

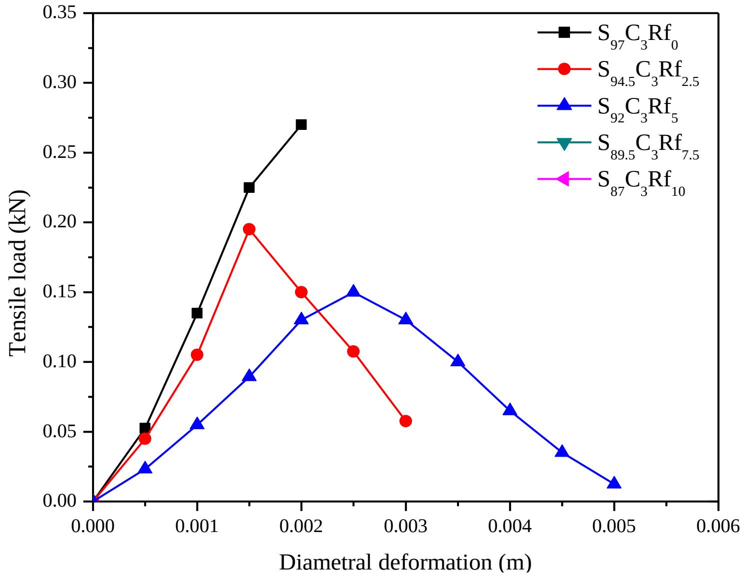

Fig. A61 Tensile load-diametral deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 14 days (Soaked condition)

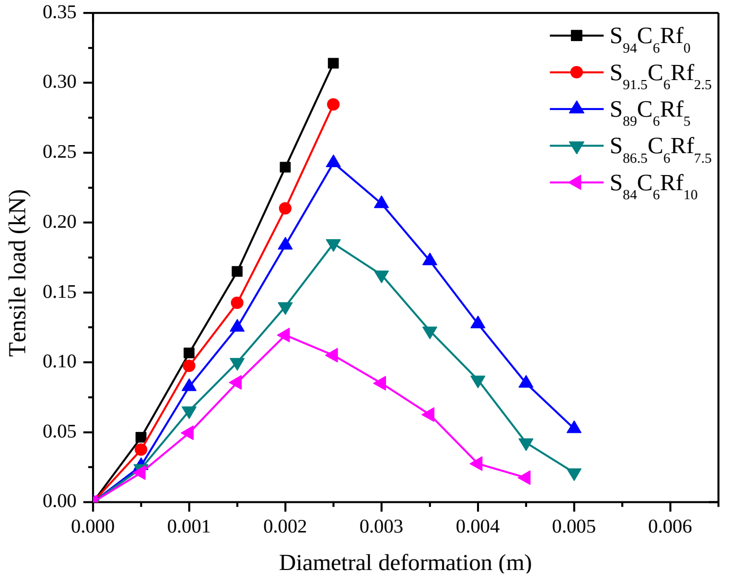

Fig. A62 Tensile load-diametral deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 7 days (Soaked condition)

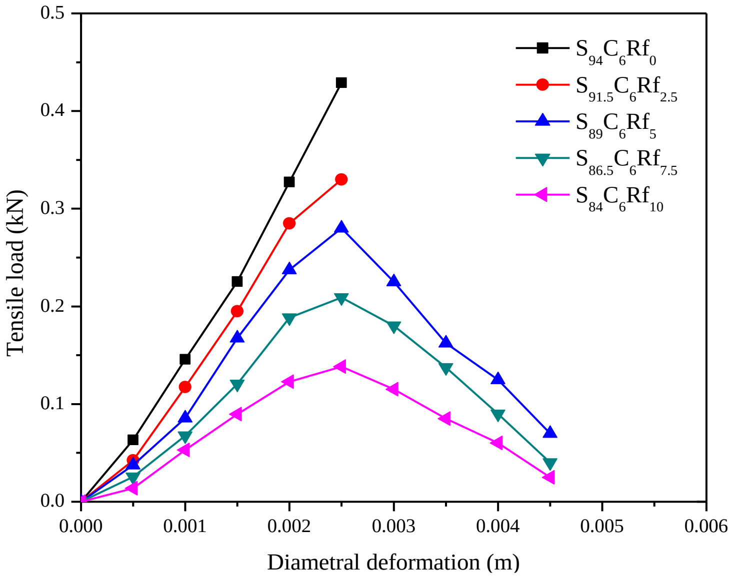

Fig. A63 Tensile load-diametral deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 14 days (Soaked condition)

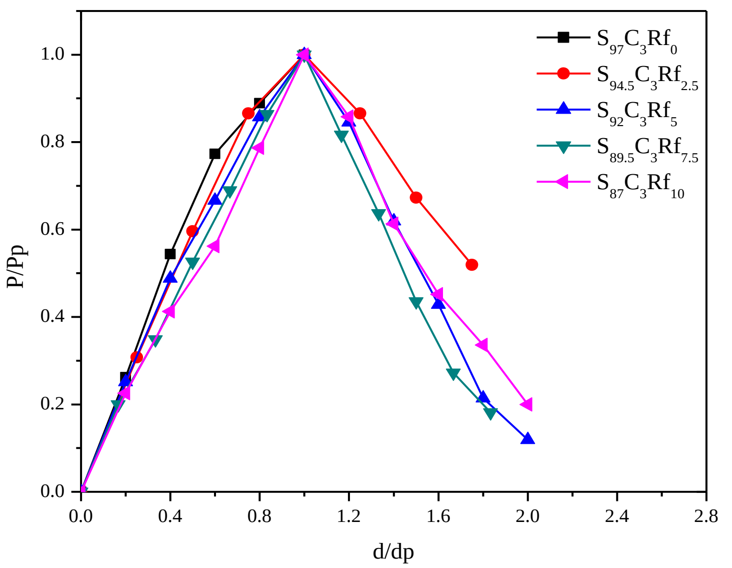

Fig. A64 Normalized tensile load-deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 7days (Unsoaked condition)

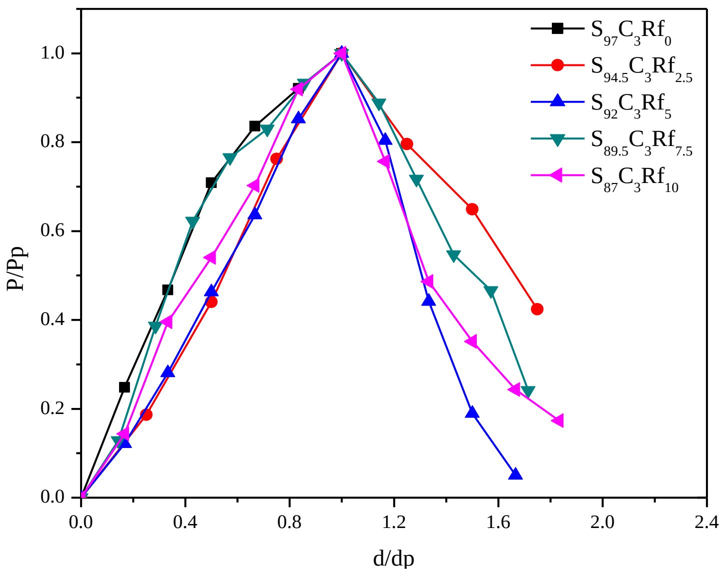

Fig. A65 Normalized tensile load-deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 14 days (Unsoaked condition)

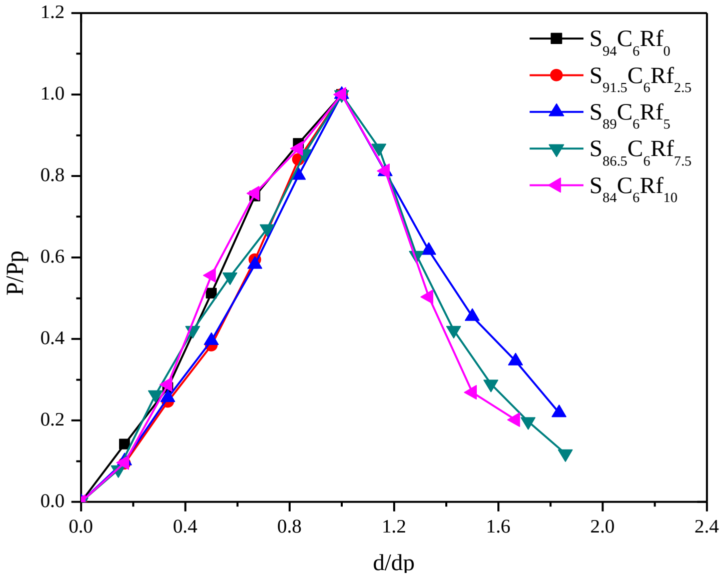

Fig. A66 Normalized tensile load-deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 7 days (Unsoaked condition)

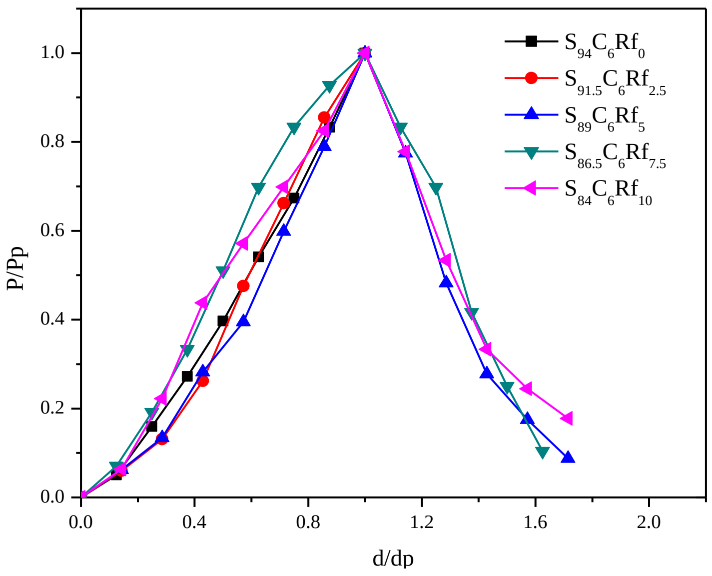

Fig. A67 Normalized tensile load-deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 14 days (Unsoaked condition)

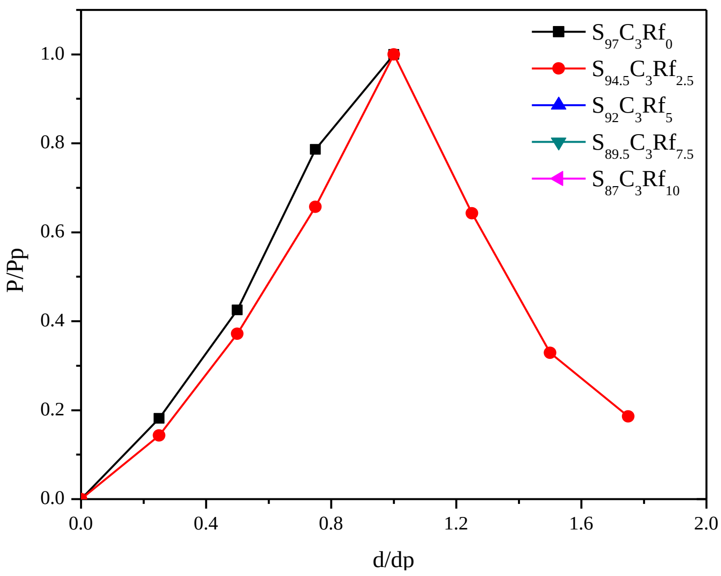

Fig. A68 Normalized tensile load-deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 7 days (Soaked condition)

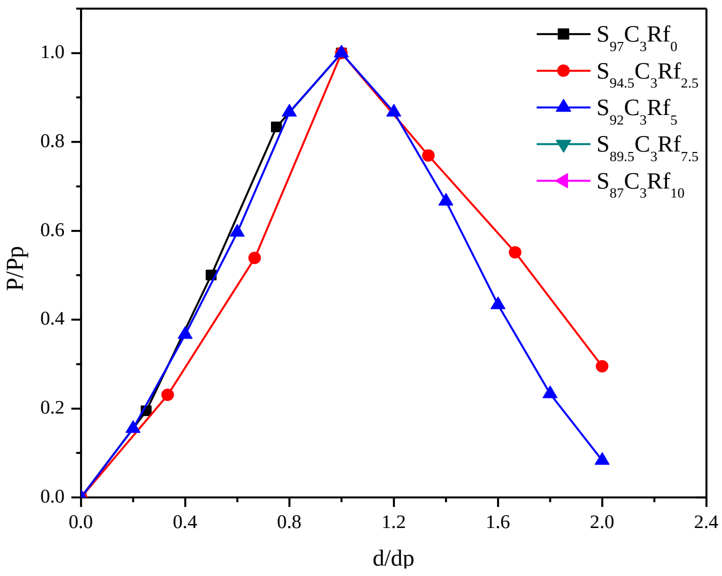

Fig. A69 Normalized tensile load-deformation curves of clayey soil mixed with 3% cement and rubber fibres and cured for 14 days (Soaked condition)

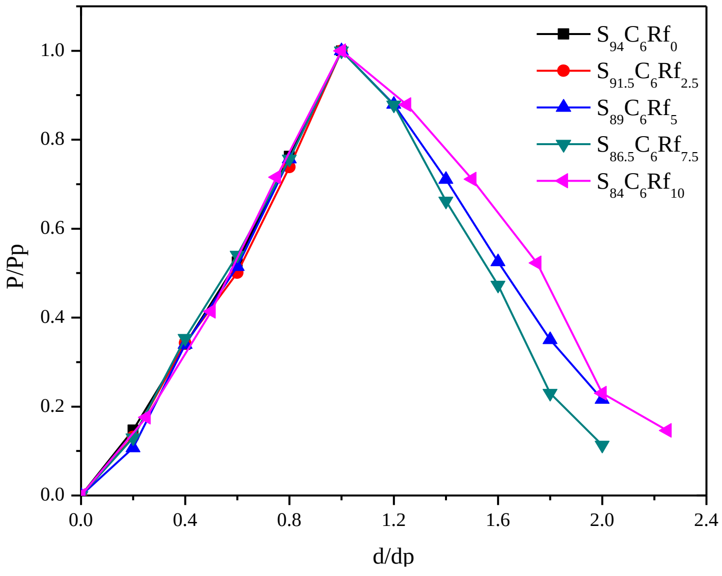

Fig. A70 Normalized tensile load-deformation curves of clayey soil mixed with 6% cement and rubber crumbles and cured for 7 days (Soaked condition)

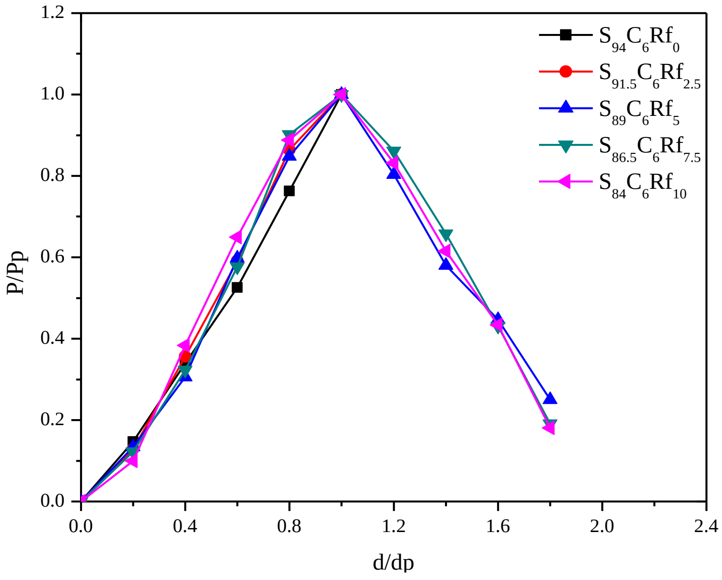

Fig. A71 Normalized tensile load-deformation curves of clayey soil mixed with 6% cement and rubber fibres and cured for 14 days (Soaked condition)

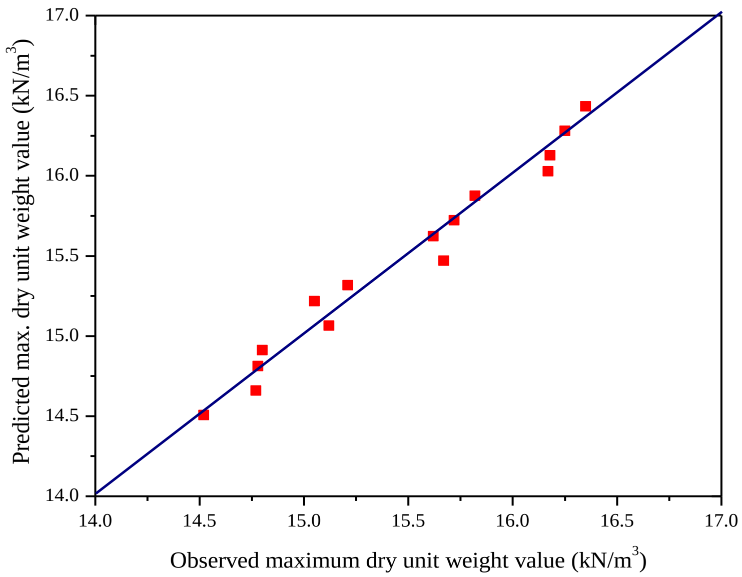

Fig. A72 Scatter plot of predicated and observed maximum dry unit weight values of clayey soil mixed with cement and rubber fibres

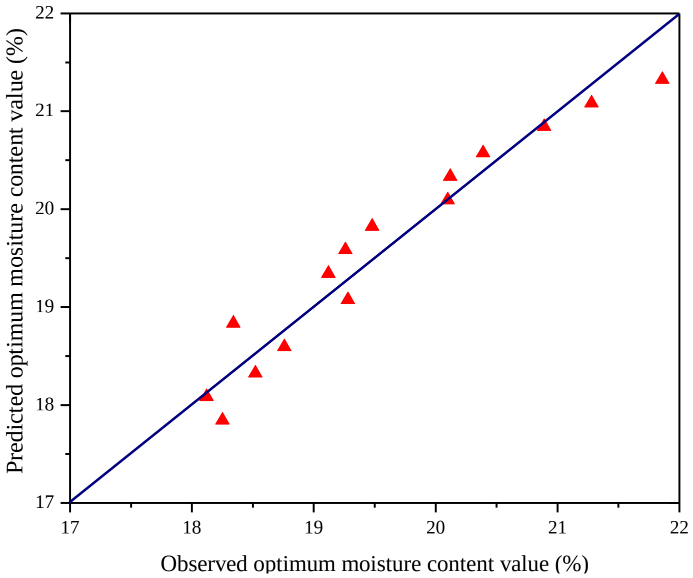

Fig. A73 Scatter plot of predicated and observed optimum moisture content values of clayey soil mixed with cement and rubber fibres

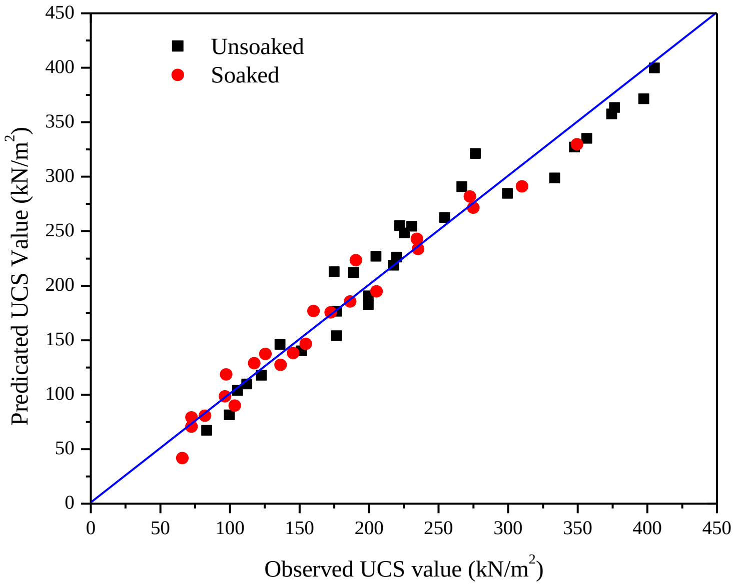

Fig. A74 Scatter plot of predicated and observed unconfined compressive strength values of clayey soil mixed with cement and rubber fibres

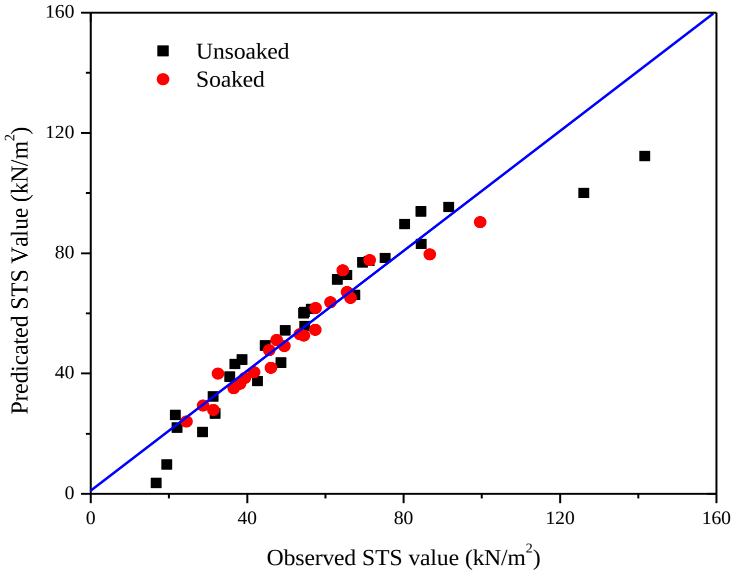

Fig. A75 Scatter plot of predicated and observed split tensile strength values of clayey soil mixed with cement and rubber fibres

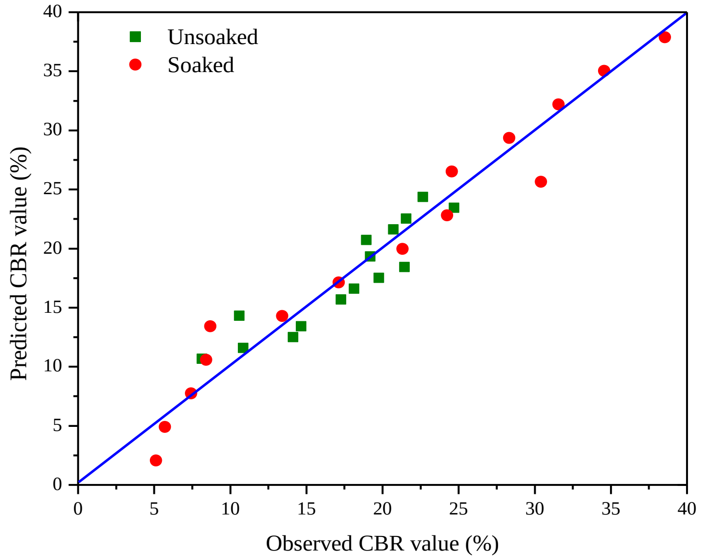

Fig. A76 Scatter plot of predicated and observed California bearing ratio (%) of clayey soil mixed with cement and rubber fibres

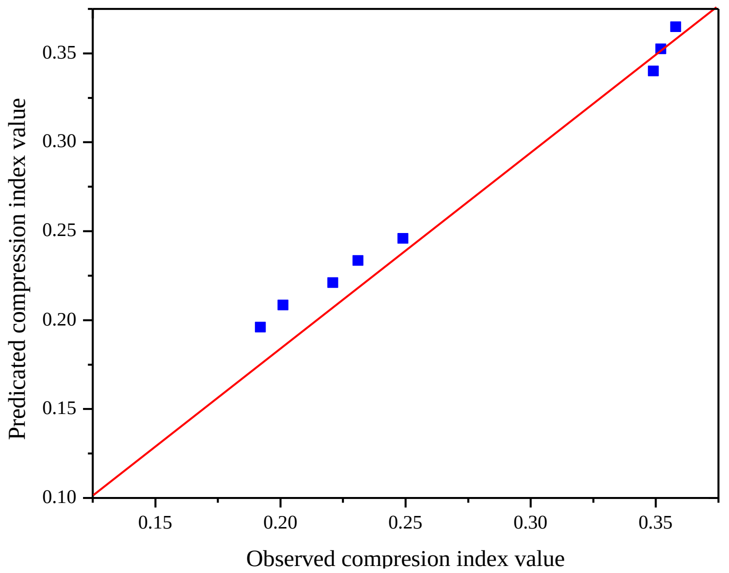

Fig. A77 Scatter plot of predicated and observed compression index values of clayey soil mixed with cement and rubber fibres

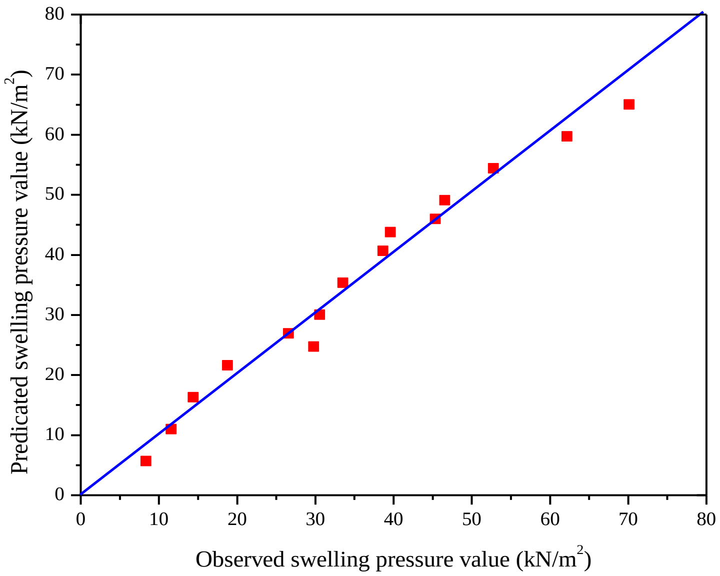

Fig. A78 Scatter plot of predicated and observed swelling pressure values of clayey soil mixed with cement and rubber fibres

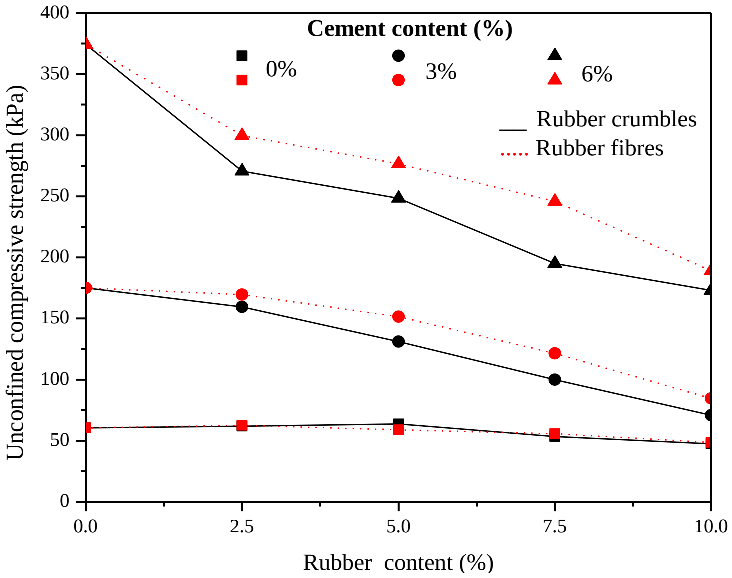

Fig. A79 Variation of unconfined compressive strength with rubber content for different cement contents (Unsoaked condition-7days cured)

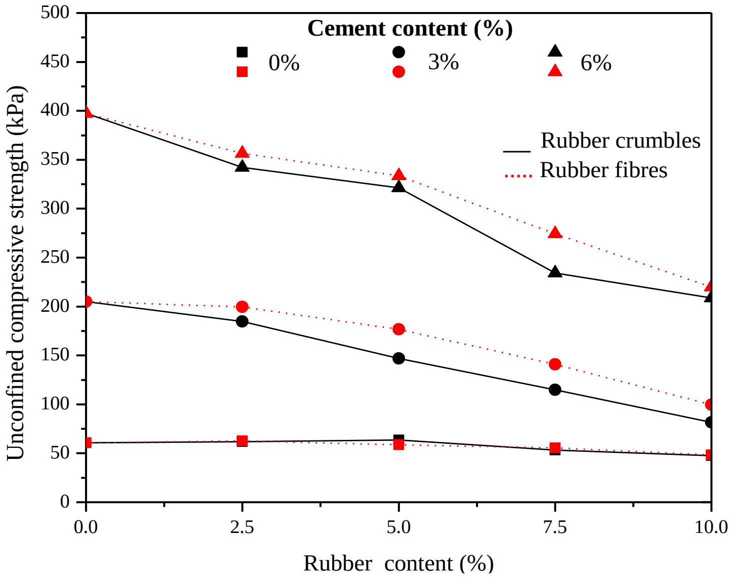

Fig. A80 Variation of unconfined compressive strength with rubber content for different cement contents (Unsoaked condition-14 days cured)

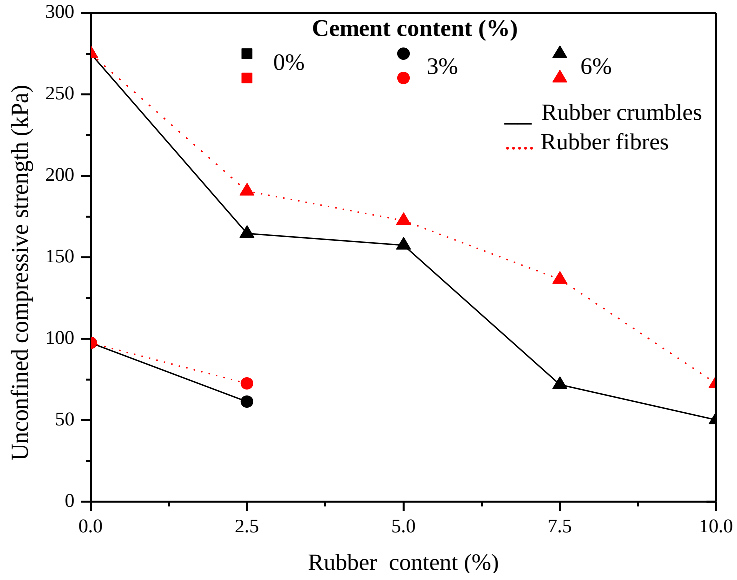

Fig. A81 Variation of unconfined compressive strength with rubber content for different cement contents (Soaked condition-7 days cured)

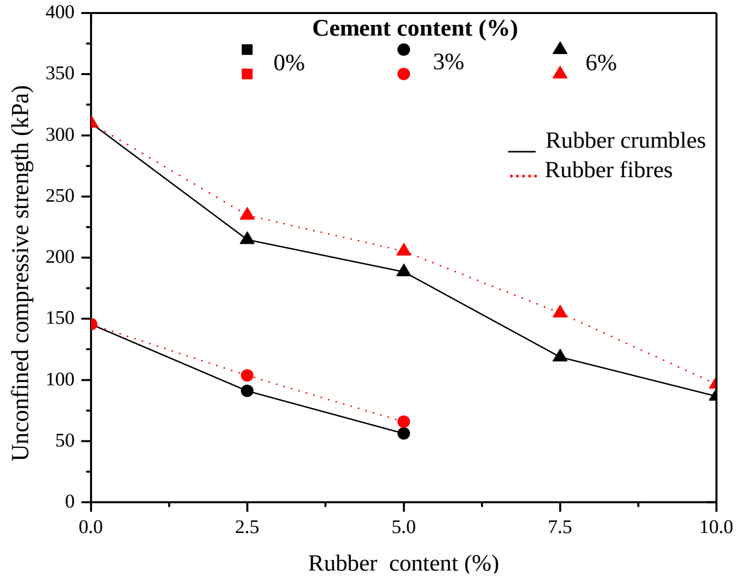

Fig. A82 Variation of unconfined compressive strength with rubber content for different cement contents (Soaked condition-14 days cured)

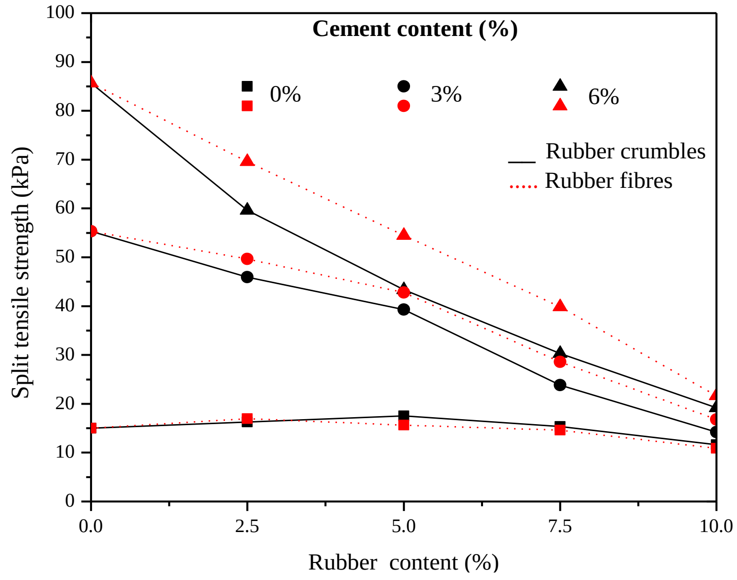

Fig. A83 Variation of split tensile strength with rubber content for different cement contents (Unsoaked condition-7 days cured)

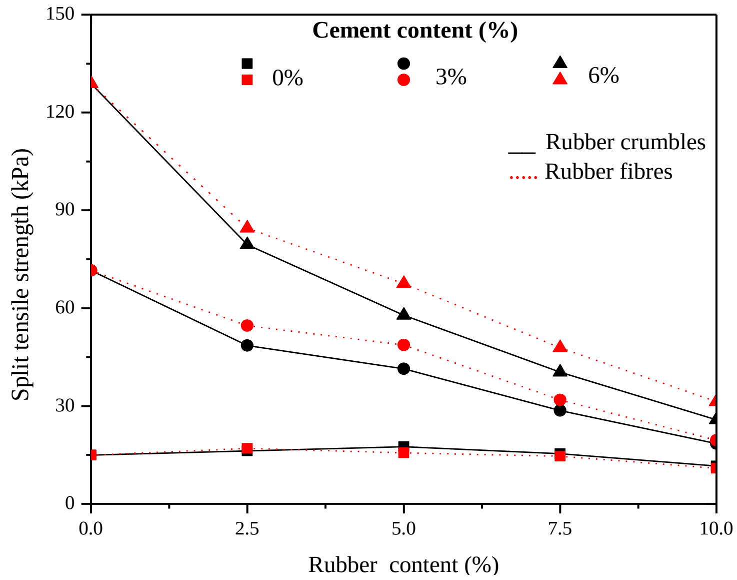

Fig. A84 Variation of split tensile strength with rubber content for different cement contents (Unsoaked condition-14 days cured)

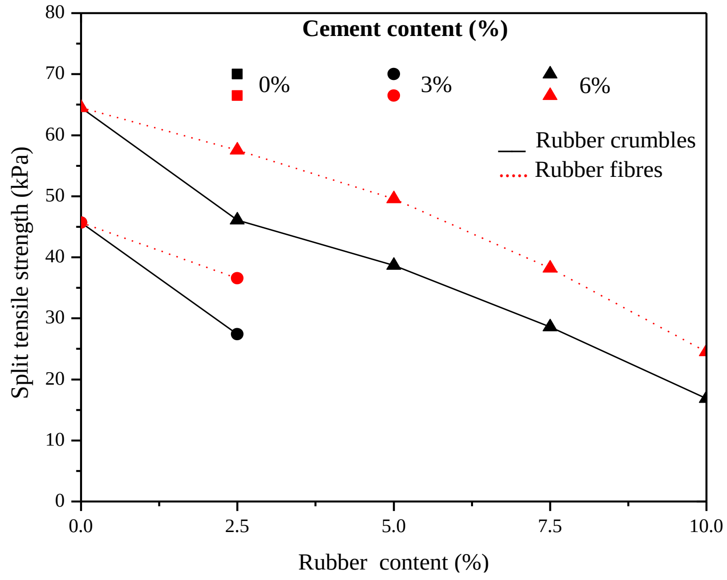

Fig. A85 Variation of split tensile strength with rubber content for different cement contents (soaked condition-7 days cured)

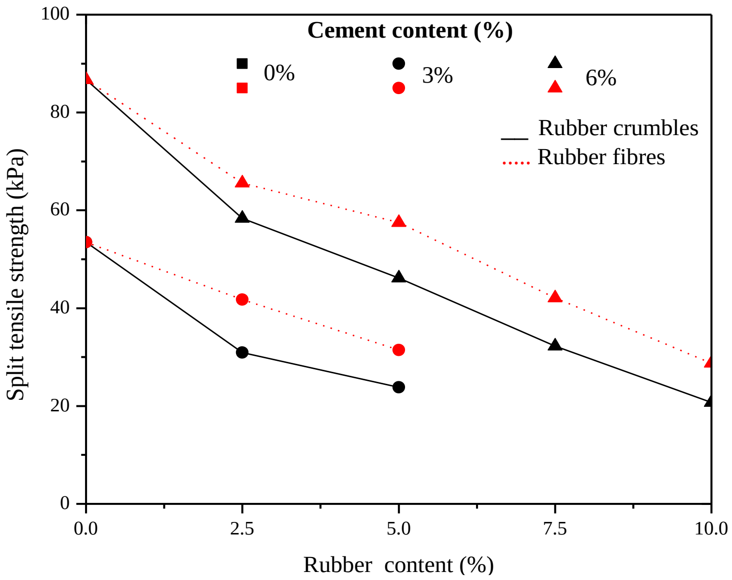

Fig. A86 Variation of split tensile strength with rubber content for different cement contents (soaked condition-14 days cured)

BIODATA AND RESEARCH PUBLICATIONS

Jitendra Singh Yadav was born on 20th March 1987 in Rewari district of Haryana, India. He received his Bachelor's degree in Civil Engineering in the year 2011 from DAVIET, Jalandhar, India. He earned his Master's degree in Structure and Construction Engineering from Dr. B. R. Ambedkar National Institute of Technology Jalandhar, India in year 2013. In July 2014, he enrolled in the Department of Civil Engineering at Malaviya National Institute of Technology Jaipur (Rajasthan), India to pursue his Ph.D. degree.

Publications out of this thesis

Journals

1. J.S.Yadav and S.K.Tiwari (2017), "Effect of waste rubber fibres on the geotechnical properties of fine grained soil stabilized with cement" *Applied Clay Sciences*, DOI: 10.1016/j.clay.2017.07.037 *(SCI Indexed-Elsevier, I.F. 3.641)*
2. J.S.Yadav and S.K.Tiwari (2017) "Evaluation of the strength characteristics of cement stabilized clay-crumb rubber mixtures for its sustainable use in geotechnical applications", Journal of Environment, Development and Sustainability DOI: 10.1007/s10668-017-9972-2 *(SCIE Indexed-Springer, I.F. 1.379)*
3. J.S.Yadav and S.K.Tiwari (2017) "Influence of Crumb Rubber on the Geotechnical Properties of Clayey Soil", Journal of Environment, Development and Sustainability DOI: 10.1007/s10668-017-0005-y *(SCIE Indexed-Springer, I.F. 1.379)*
4. J.S.Yadav and S.K.Tiwari (2017) A study on the potential utilization of crumb rubber in cement treated soft clay. Journal of Building Engineering. Volume 9, January 2017, Pages 177–191 *(SCI Indexed-Elsevier, I.F. 1.055)*
5. Yadav, J. S., & Tiwari, S. K. (2017). The impact of end-of-life tires on the mechanical properties of fine-grained soil: A Review. Environment, Development and Sustainability, 1-84. *(SCIE Indexed-Springer, I.F. 1.379)*
6. J.S.Yadav and S.K.Tiwari (2017) "Assessment of geotechnical properties of uncemented/cemented clayey soil incorporated with waste crumb rubber." Journal of Materials and Engineering Structures «JMES» 4.1 (2017): 37-50
7. J.S.Yadav and S.K.Tiwari (2016) "Effect of inclusion of crumb rubber on the unconfined compressive strength and wet-dry durability of cement stabilized clayey soil" Journal of Building Materials and Structures, 3(2), 68-84.

Under Review

1. J.S.Yadav and S.K.Tiwari "Strength Characteristics of cemented clay containing rubber crumbles and fibres: A comparative study" (Under review, Manuscript no:- JRMGE_2017_225_Original_V0)

Conferences

1. J.S.Yadav and S.K.Tiwari, "Strength and Swelling pressure studies on the utilization of rubber tire wastes in clayey soil" , 6th Indian Young Geotechnical Engineers Conference, 10-11 March 2017, NIT Trichy, India.
2. J.S.Yadav and S.K.Tiwari "Experimental Investigation of Geotechnical Properties of Clay-Rubber Crumbles Mixtures", 3rd International Conference on Sustainable Energy and Built Environment, 16-17 March 2017, VIT Vellore, India.
3. J.S. Yadav and S.K. Tiwari, **"**Strength and Durability aspects of cement stabilized clayey soil containing waste crumb rubber**"** TRACE -2016 held at Amity School of Engineering & Technology, Amity University Uttar Pradesh, Noida from 11th-12th August 2016.
4. J.S.Yadav, and S.K.Tiwari "Evaluation of strength characteristics of cement stabilized clayey soil containing rubber tire wastes under tensile stresses", Indian Geotechnical Conference 2017-GeoNEst, 14-16 December 2017, IIT Guwahati
5. J.S.Yadav, & S.K.Tiwari "Evaluation of strength characteristics of cement stabilized clayey soil containing rubber crumbles under tensile stresses". 2nd International Conference_ ACSGE 2018, 26-28 Feb, 2018, BITS Pilani.
6. J.S.Yadav, & S.K.Tiwari " A Study on Strength Behavior of Clay-Rubber Fibres Mixtures". 2nd International Conference_ ACSGE 2018, 26-28 Feb, 2018, BITS Pilani.
7. J.S.Yadav, & S.K.Tiwari "Experimental Investigation of Geotechnical Properties of Clay-Rubber Fibres Mixtures". Environmental Geotechnology, Recycled Waste Materials and Sustainable Engineering, March 29-31, 2018, NIT Jalandhar.